EARLY HEIGHT GROWTH PATTERNS OF PLANTED WHITE SPRUCE

SEEDLINGS IN INTERIOR ALASKA

By

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EARLY HEIGHT GROWTH PATTERNS OF PLANTED WHITE SPRUCE SEEDLINGS IN INTERIOR ALASKA

A

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ABSTRACT

This study looked at early height growth of planted white spruce *Picea glauca* (Moench) Voss around the Fairbanks area. The effort focused on two Levels-of-Growing-Stock (LOGS) experimental plantations located in the Bonanza Creek Experimental Forest that incorporated an espacement study. Annual total height was also measured on 16 operational plantations and then compared to LOGS plantations. Average annual total height at Site 2 of the LOGS plantations was significantly greater than at Site 1. A significant difference in height growth between these sites was attributed to differences in aspect. Results showed significant annual total height differences among the espacement plots within the LOGS plantations. The narrowest spacing 1.2 X 1.2 m and widest spacing 3.7 X 3.7 m showed a lower annual total height while spacings 1.8 X 1.8 m, 2.4 X 2.4 m, and 3.0 X 3.0 m showed a greater annual total height at age ten. The range of annual total height found at the LOGS sites was not significantly different than the range of annual total height found at the 16 operational plantations. Additionally, path analysis was used to quantify the direct and indirect effects of multiple environmental variables (i.e., percent slope, slope position, competition, aspect, and soil moisture) on growth rate at the operational plantations. It was found that slope position, percent slope, and competition had significant direct effects on growth rate. These results provide insight for resource managers when predicting the height growth of planted white spruce.

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I would like to dedicate this thesis to my mom, Rosemary. Mom, it may take me a long time to finish things, but when I start them, I DO get them done. Hope it makes a good read….

I. INTRODUCTION

A. Problem Statement

A major concern of forest managers is the ability to regenerate forest stands that were previously harvested or damaged by natural disturbances such as fire. In the Fairbanks area of interior Alaska these regeneration concerns are great because white spruce (*Picea glauca* (Moench.) Voss), a comparatively slow regenerator, is the only major commercial tree species (Yarie and Van Cleve 1983). Therefore, management plans in interior Alaska commonly depend on successful regeneration of planted white spruce after harvesting.

Considerable work has been done concerning regeneration of white spruce throughout Canada (e.g., Mullin 1966; Eis 1967; Stiell 1976). The earliest experimental plantations in Canada were established in the 1920's (Stiell 1955); in addition, the Great Lakes Region of the United States has contributed to white spruce regeneration research (Rudolf 1950). However, only a limited amount of applied work has been completed regarding white spruce regeneration in interior Alaska (e.g., Fox et al. 1984; Wurtz 1988; Packee 1990; Youngblood and Zasada 1991). This effort focuses on using early height growth of planted white spruce seedlings to determine the effects of espacement and site characteristics.

B. Objectives

The objectives of this thesis are two-fold: 1) to address the effects of espacement (stem density at time of planting) on total annual height growth of white spruce planted in two experimental plantations in interior Alaska and 2) to compare annual total height growth on local operational plantations with the experimental plantations as well as to determine the contribution of a suite of site characteristics on height growth rates of white spruce in interior Alaska. This information will aid in predicting early height growth rates in interior Alaska, contribute to adjustments to site index curves, and aid interior Alaska forest managers in determining where harvesting and regeneration should be done.

To accomplish these objectives two phases of research were conducted:

Phase one – Experimental espacement

This phase was designed to determine the effects of initial espacement on annual total height of white spruce using two research plantations located west of Fairbanks, Alaska. These plantations were planted in spring of 1986 and have been continually monitored to provide long-term data of early height growth trends. Trends on these sites should show the effects of initial espacement and, because of the high quality of plantation maintenance, should also provide a maximum growth potential of planted white spruce in interior Alaska.

Phase two – Operational Plantations

This phase of research was designed to determine the effects of location and site conditions on height growth rates of white spruce among operational plantations near Fairbanks, Alaska, by using annual total height data collected in July of 1998 from 18 plantations. Height growth rates occurring on these plantations should show the effect of site, environmental variables, and combinations there of.

II. LITERATURE REVIEW

A. *Why study white spruce?*

White spruce (*Picea glauca*), also known as Canadian spruce, skunk spruce, cat spruce, Black Hills spruce, western white spruce, Alberta white spruce, and Porsild spruce, is adapted to a wide range of edaphic and climatic conditions of the Northern Coniferous Forest. The wood of white spruce is light, straight grained, and resilient. It is used primarily for pulpwood and as lumber for general construction (Nienstaedt and Zasada 1990).

White spruce is one of the most widely occurring conifer species in North America (Nienstaedt 1957). It is transcontinental in distribution and grows under a wide range of climatic conditions (Nienstaedt and Zasada 1990). White spruce runs westward from Newfoundland across Canada along the northern limit of trees and almost reaches the Arctic Ocean in the Mackenzie District of Northwest Territories (Sutton 1969). White spruce extends south through British Columbia and east through Alberta and Manitoba to Lake Winnipeg and then south and east through northern Minnesota and Wisconsin, northeastern New York, and Maine (Nienstaedt and Zasada 1990) (Figure 2.1). In Alaska, white spruce reaches the Bering Sea at Norton Bay and the Gulf of Alaska at Cook Inlet (Figure 2.2). Because of its transcontinental distribution, it is a major commercial species throughout the boreal regions of North America (Wurtz 1988).

Natives of boreal regions used white spruce for heating, building, and medicinal purposes for approximately the last 12,000 years (Hultén 1968), and the importance of this tree has persisted. The town of Fairbanks was founded in 1901 (Wurtz 1988) and relied heavily on white spruce wood for heating, fuel for riverboats, and construction. In

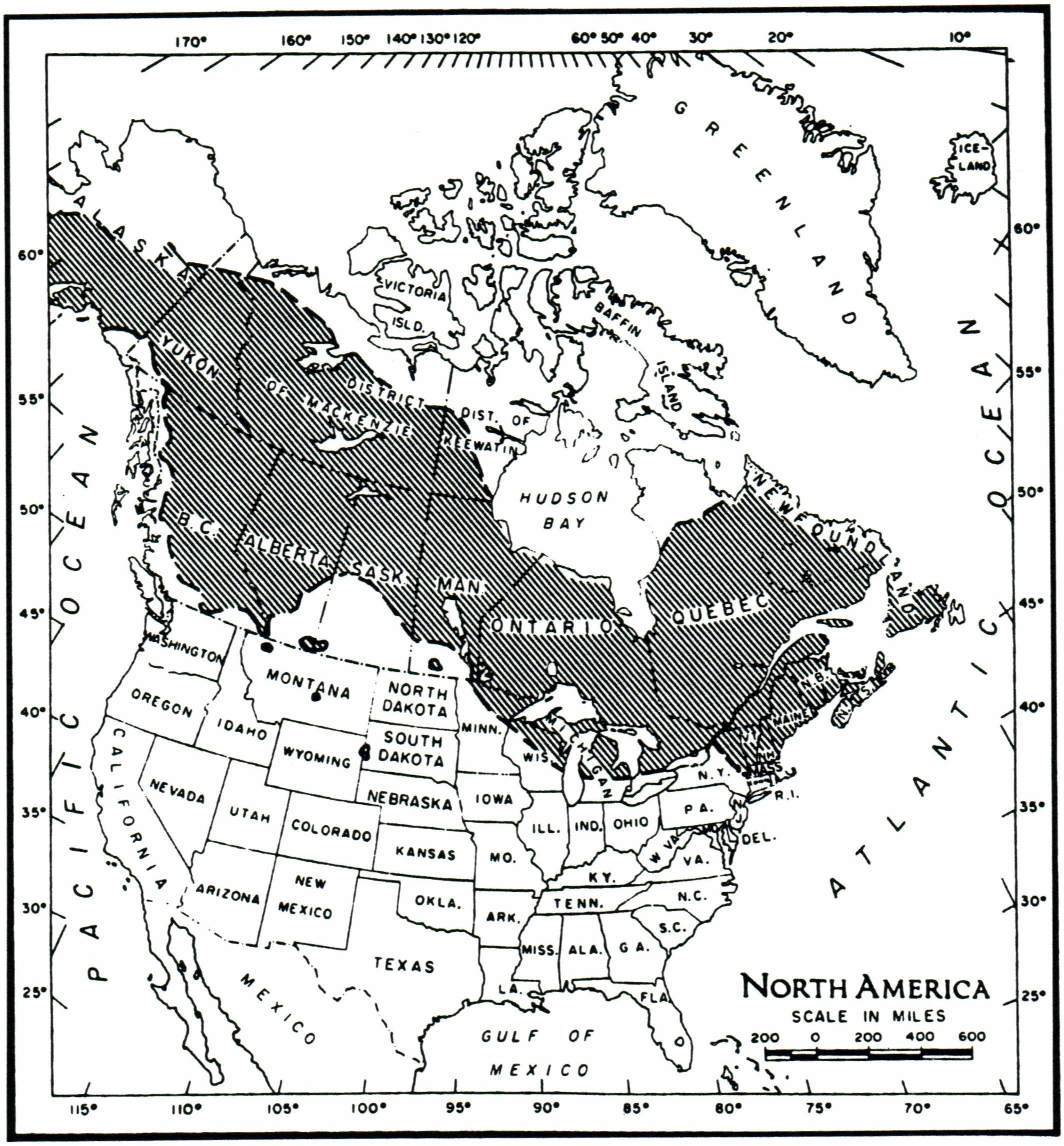

Figure 2.1. The botanical range of white spruce (Sutton 1969).

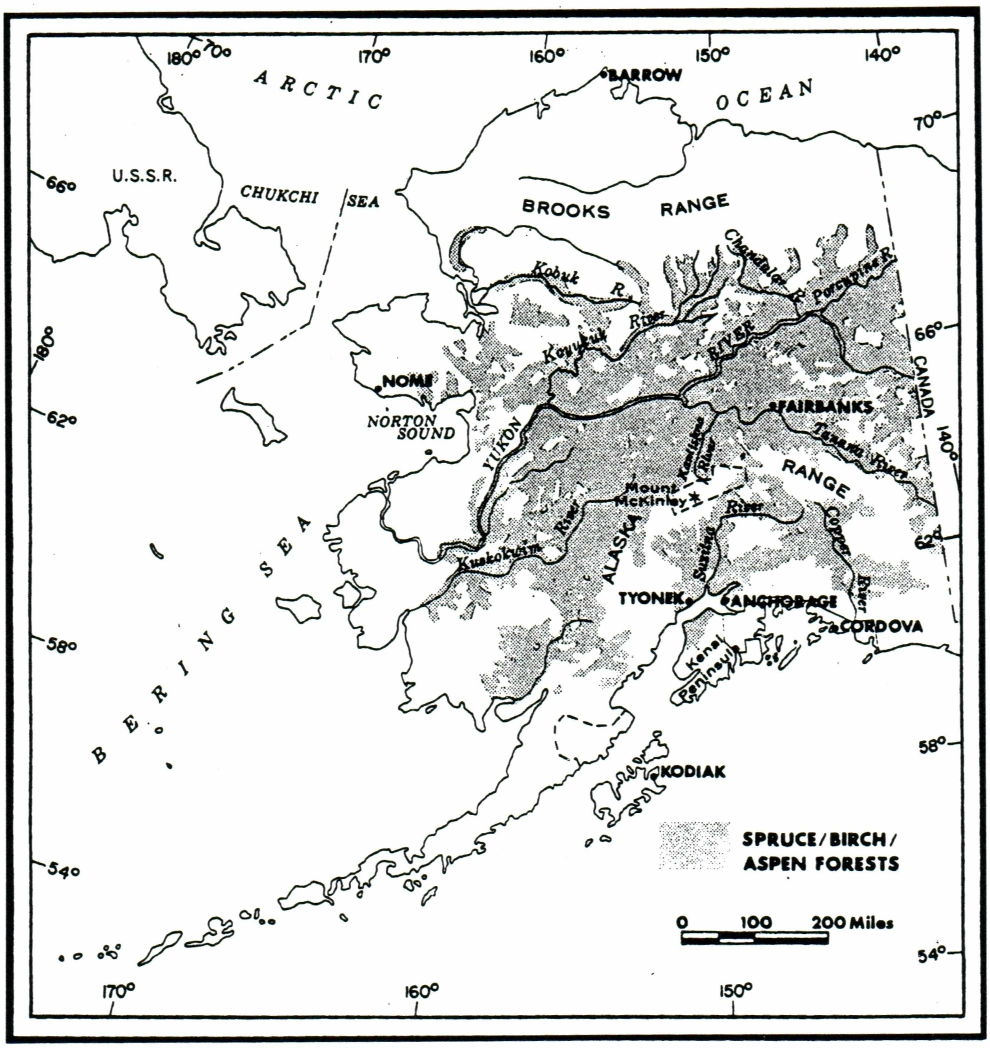

Figure 2.2. Distribution of forested lands throughout interior Alaska (Zasada 1976).

interior Alaska, man has influenced the distribution of white spruce immensely, especially after the gold rush in the early 1900s. Although today the amount of white spruce harvested in the Fairbanks area has decreased (Alaska Department of Natural Resources 1988), overall the use of interior white spruce is still important.

Therefore, white spruce has been the focus of much past and present research. Farr developed growth and yield tables for white spruce in 1967. Gregory and Wilson (1968) compared the cambial activity of white spruce from Alaska with that from Massachusetts. They found that the period of time in which diameter growth occurs for Alaskan white spruce is one-half as long as that for Massachusetts' white spruce. Yarie and Van Cleve (1983) determined that above ground standing biomass of white spruce in mature stands ranges from 0.92 to 23.28 kg/m^2 and current annual production ranges from .089 to 2.853 kg/m^2/a in interior Alaska.

B. *Why study interior Alaska?*

Alaska's interior forests are similar to those found in Finland, Norway, and Sweden. Productivity is adequate for forestry to be considered a legitimate land use. Current research indicates that stands can be regenerated. Silvicultural practices developed in other northern forests should be evaluated to determine their applicability in the taiga (Zasada 1976).

Northern boreal forest systems are unique in their ability to develop under extreme environmental conditions. Interior Alaska provides an opportunity to study these boreal forests. The following summarizes descriptions of this region by (Van Cleve et al. 1996) and (Zasada 1976). Interior Alaska is bounded on the south by the Alaska Range and on the north by the Brooks Range. The Alaska Range runs from the Canadian boarder southwest for 1000 km to the Aleutian Range. The regional climate is strongly continental because of extreme temperature ranges and low annual precipitation. The Alaska Range effectively blocks the moist warm coastal air masses; Fairbanks averages 27 cm of precipitation with approximately 35% falling as snow that remains as a permanent cover from mid-October through April.

Areas of high latitude experience low sun angles as well as extreme seasonal changes in temperature and day-length. Temperatures in interior Alaska range from less than –50° C to +35° C; average daily temperatures in January are –25° C and +17° C in July with an average annual temperature of –4° C. Day length, the amount of time between sunrise and sunset, at high latitudes changes drastically with the seasons. In Fairbanks, 65° N latitude, day length at winter solstice is 3 hours and 42 minutes with a maximum sun angle of 1.5°. Day length at the summer solstice is 21 hours and 50 minutes with a maximum sun angle of 48.5°.

Forest soils in interior Alaska are shallow and poorly developed. On river bottoms in the Tanana Valley, soils are relatively coarse textured and the parent material is alluvial in origin. Upland soils are fine textured and typically formed from loess deposits. The organic matter covering the soils represents a much larger portion of the forest biomass than in similar forests at lower latitudes.

Interior Alaska is a region of discontinuous permafrost. Permafrost is found where soil temperatures are perennially at or below 0° C, which in interior Alaska usually means north-facing slopes due to the amount of sun received, and the low solar angle. The effects that topography has on solar radiation received at the ground surface are greater than those found at lower latitudes. North-facing slopes are often dominated by black spruce (*Picea mariana* (Mill.) B.S.P.). The build-up of forest floor organic matter can cause major changes in soil temperature. Therefore, permafrost can develop on flat floodplain terraces and its presence is directly related to the age of the site. Young floodplain sites are often dominated by balsam poplar (*Populus balsamiferia* L.) while older sites are often dominated by black spruce. On south-facing, well drained, and permafrost free sites aspen (*Populus tremuloides* Michx.), paper birch, (*Betula papyrifera* Marsh.) and white spruce are often the dominant species.

Interior Alaska comprises approximately 137 million ha of forested land of which only about seven percent are considered to be commercial forest (capable of producing 1.3 cubic meters per hectare per year). The area covered by commercial forest is large when compared to the amount of land that meets the same criteria for coastal Alaska (Wurtz 1988). White spruce makes up 60 percent of this commercial land base; aspen, paper birch, and balsam poplar make up the remainder.

Silviculture practices, harvesting, and regeneration of white spruce stands in interior Alaska are limited to population centers primarily because there is little economic incentive to develop forest stands that are not easily accessible. Although there is some good silvicultural research in interior Alaska (Fox et al. 1984; Wurtz 1988; Packee 1990; Youngblood and Zasada 1991), it is limited in quantity and therefore additional research of white spruce regeneration of value.

Interior Alaska provides a unique study system because in this area white spruce reaches one of its most northern commercial and botanical limits (Zasada and Gregory

1969). White spruce occurs extensively between the Brooks Range on the north and the coastal ranges to the south. It is found throughout the Tanana Valley and is one of the two dominant conifer species in the Fairbanks area.

C. *Why study artificial white spruce regeneration?*

> White spruce is now one of the most widely planted tree species in boreal regions of North America...Forest geneticists have encouraged the planting of white spruce by assertions that its highly variable nature indicates a capacity for considerable gains through tree improvement measures (Stiell 1976).

Due to inadequate seedbeds natural regeneration of white spruce is often poor after harvest (Fox et al. 1984). Therefore, from a management perspective, when sustained timber production is the objective, artificial regeneration is often the only economically viable option. In interior Alaska direct seeding, has proven ineffective for white spruce (Youngblood and Zasada 1991). Therefore, planting of seedlings is the reasonable artificial regeneration technique.

Youngblood and Zasada (1991) studied artificial regeneration options for white spruce in interior Alaska. They found that white spruce can be successfully regenerated with no mechanical site preparation by clear-cut harvesting and then planting containerized seedlings. Early growth of planted seedlings is often slow. Also, early height growth of white spruce is not as rapid as its hardwood associates and, thus, often must compete with other vegetation early in its life cycle. In addition to being slow growing, planted white spruce seedlings often demonstrate signs of planting check. This can be detected by either slower than normal height growth or discoloration of the needles (Mullin 1963). Planting check can result from improper planting depth, damage to roots during planting, limitations of adequate nutrient supply, excess or deficient moisture, competition with other plants, or low temperatures (Brace 1964; Eis 1965; Dobbs 1976; Nienstaedt and Zasada 1990). These situations can occur as a result of poor economic conditions that limit the possibility for appropriate harvest practices, site preparation, and good planting practices. White spruce has an advantage later in its life cycle because it is shade tolerant and is able to eventually overtake or replace competing vegetation on good sites due to its long life span (Putman 1985).

D. *Why study height growth?*

White spruce demonstrates strong apical dominance, which is a species ability to expend more energy to grow in a vertical direction rather than a lateral direction. Therefore, height growth trends are good indicators of site quality and regeneration success (Thomson and McMinn 1989). Unfortunately, time (in years) to reach breast height, the standard measurement point is relatively undocumented. In addition, current yield tables for interior Alaska by Farr (1967) lack the first years of development for site index curves.

Early height growth trends are important for a number of reasons. Firstly, measurements of height growth and determination of survival are the two primary ways researchers have to assess plantation success. Height growth allows easy comparison with other studies, since height measurements are relatively homogeneous no matter where and when they were taken. Height is a measure that is also used to describe mature trees and how well they are growing over time (site index). Studying early height growth trends of white spruce after planting is essential to resource managers in developing land use plans and for determining rotation ages and annual allowable cut estimates for interior Alaska.

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III. PHASE ONE: ESPACEMENT-EXPERIMENTAL

A. Introduction

Forest managers share a major concern, the cost of regeneration following harvest or the loss of a natural stand due to a disturbance (Packee 1990). Therefore, management objectives for an area must be clearly defined prior to regeneration activities. For example, determining the best species for an area and espacement (density at time of planting) are major elements in the successful planning and management of future forest stands (Lavender et al. 1990). Planting too many trees can be uneconomical due to the amount of money spent on planting and later stand maintenance; whereas planting too few trees can be uneconomical due to lack of sufficient volume (Johnstone 1999).

Although the influence of espacement on the growth and development of white spruce plantations is understood conceptually (e.g., Pollack et al. 1992; Berry 1987), few data sets are available to verify early height growth trends. Interior Alaska forest management would greatly benefit from a better understanding of early height growth trends for the economically viable species, white spruce.

In 1984, the Agricultural and Forestry Experiment Station, of the School of Agriculture and Land Resources Management at the University of Alaska Fairbanks, began the forest growth and yield program to study interior Alaskan forests (Packee 1984). One aspect of this project is stand density regulation and is referred to as the

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Hollingsworth, J. and Packee, E.C. (prepared for submission to Canadian Journal of Forestry Research) *Picea glauca* height growth at five different espacements in interior Alaska: Ten year results.

Levels-of-Growing-Stock (LOGS) study. Overall objectives of the LOGS project are to examine two major effects: 1) initial espacement and 2) pre-commercial and commercial thinning. Objectives of this research are to determine the effect of site and initial espacement on the annual total height of planted white spruce seedlings.

B. Methods

1. Study Area

The two study sites are located within the Bonanza Creek Experimental Forest (Latitude 64° 44' N, Longitude 148° 18' W), approximately 20-km southwest of Fairbanks, Alaska (Figure 3.1). Both sites are on well-drained, permafrost free soils classified as Alfic cyrochrepts belonging to the Fairbanks Silt Loam soil series (Selkregg 1974). Elevation at these sites ranges from 250 to 300 m with an average slope of 10 percent. In May 1983, prior to the establishment of the LOGS sites, a wildland fire severely burned the area killing all trees.

Site I is located on a southerly aspect (175° – 190°) and prior to the fire was dominated by mature white spruce; after the fire it began regenerating naturally to trembling aspen (*Populus tremuloides* Michx.). Site II is located on a northeasterly aspect (40° – 50°) and prior to the fire was dominated by mature white spruce and paper birch (*Betula papyrifera* Marsh.); after the fire it began regenerating naturally to bluejoint reedgrass (*Calamagrostis canadensis* (Michx.) Beauv.).

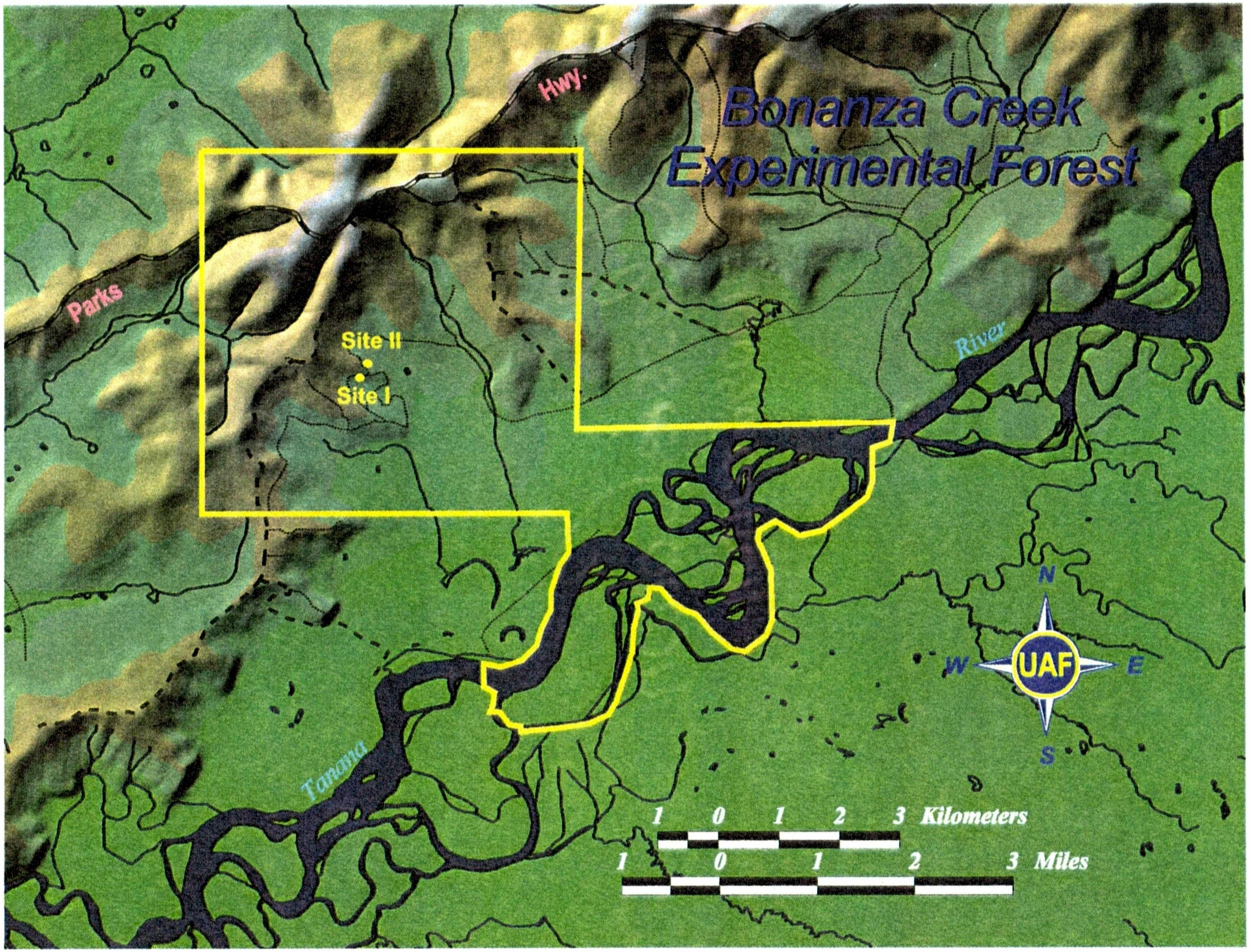

Figure 3.1. Locations of LOGS study sites at the Bonanza Creek Experimental Forest.

2. Site Preparation

During the summer of 1985, both sites were prepared for planting. Remaining standing trees where harvested and mineral soil was exposed by scarifying with a TTS-35 disc trencher. In 1986, seedlings were hand-planted during the Memorial Day weekend by Boy Scouts from Troop 10 Fairbanks. Seedlings were one-year-old container stock provided by the Alaska State Nursery. Competing vegetation (aspen and alder (*Alnus crispa* (Ait.) Pursh), and birch and alder on Site I and II, respectively) was cut in the summers of 1991 and 1994 to ensure that seedlings were free to grow without the effects of above ground woody competition.

3. Design and Block Layout

The experiment was arranged randomly at the two different sites. Each site was divided into three replication blocks: Rep A, Rep B, and Rep C; within each replicate five espacement plots were randomly established: 1.25 X 1.25, 1.75 X 1.75, 2.50 X 2.50, 3.00 X 3.00, and 3.75 X 3.75 meters, referred to as spacings 1, 2, 3, 4, and 5, respectively (Figure 3.2). Within each espacement plot two areas were specifically defined: a measurement area (20 X 20 m) where all experimental measurements were taken and a buffer area (10 m) that was planted at the same density as the measurement area with the purpose of minimizing edge effects (Figure 3.3).

4. Measurements

Annual total height of each seedling within the measurement area was measured since establishment of the sites. The number of seedlings varied within each measurement area of the espacement plot (spacing 1 had 256 seedlings, spacing 2 had

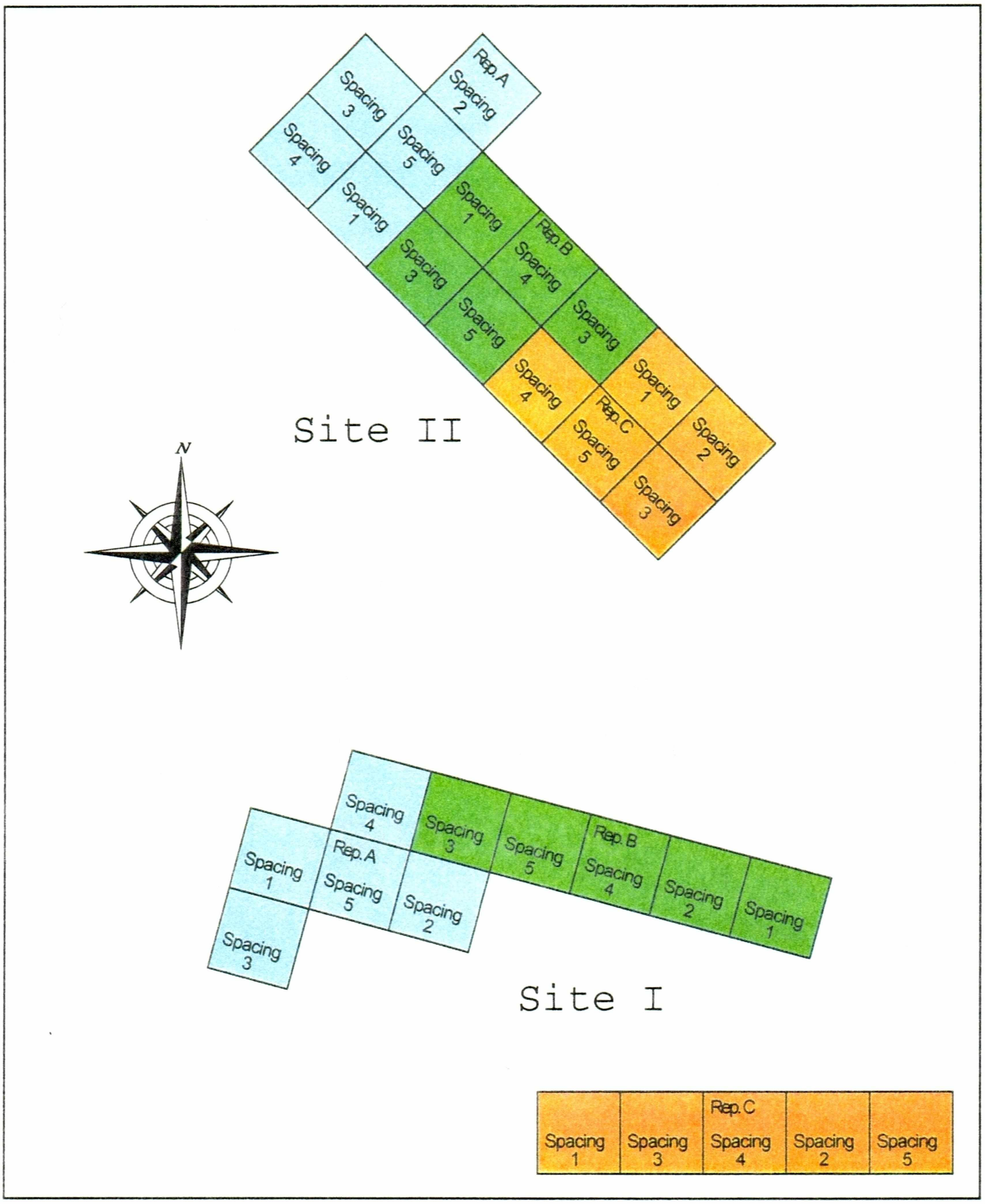

Figure 3.2. Site I and site II in the Bonanza Creek Experimental Forest showing layout of sites, replications, and espacement plots.

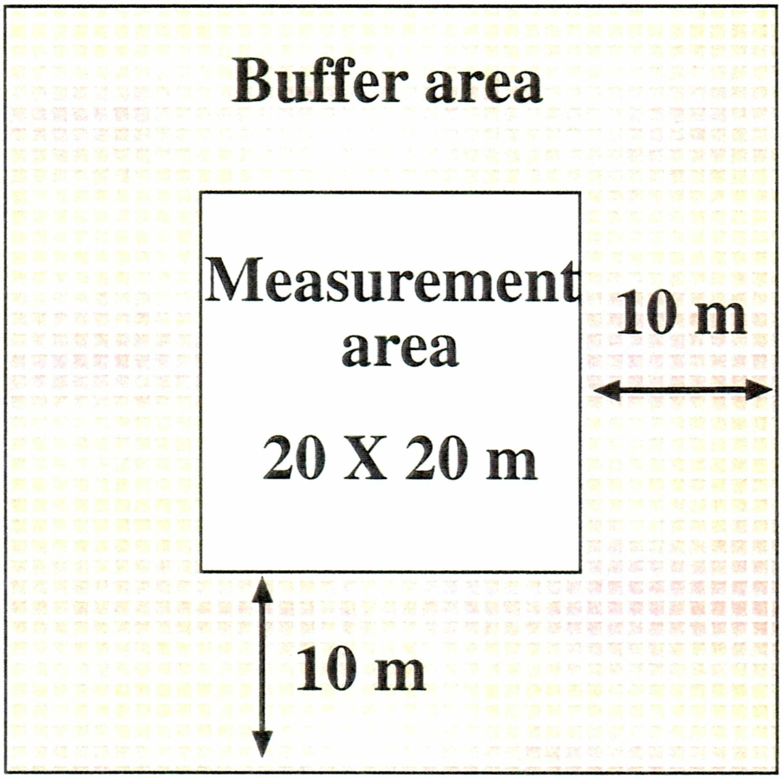

Figure 3.3. Layout of the sampling area within each espacement plot. The measurement area is where all experimental measurements were taken and the buffer area was planted at the same spacing to minimize edge effect and also used as a source to replace dead seedlings in the measurement area.

121 seedlings, spacing 3 had 64 seedlings, spacing 4 had 49 seedlings, and spacing 5 had 36 seedlings). Annual measurements were made from the ground surface to the top of the terminal bud of the seedling. Measurements were made using a measuring rod graduated in one-centimeter units and taken to the nearest centimeter. Survival was determined as either dead or alive based on visual observation. During the first five years after initial planting dead trees were replaced, with seedlings from within the buffer area.

5. Statistical Analyses

All statistical analyses were completed using SAS version 6.1. Due to unbalanced sample sizes within each site, spacing, and replication, the use of the simple SAS procedure for Analysis of Variance (ANOVA) was not possible (SAS 1985). The SAS General Linear Model (GLM) was selected as the appropriate approach. The GLM procedure for ANOVA is especially useful with unbalanced data sets. ANOVA is a single test for comparing multiple means. The major assumptions of ANOVA are (i) data are normally distributed, (ii) variances within the data are equal, and (iii) samples are independent of each other. The data were tested using the SAS univariate procedure, and met two of the three assumptions of ANOVA. The data were found to be normally distributed and had equal variances; however, because annual total height is not independent of year (i.e., height of white spruce increases as seedlings get older), data were analyzed separately by year. Plot was chosen as the experimental unit because variability was much larger within blocks than due to blocks. Although ANOVA tests to determine whether there are significant differences among the plot means, it does not imply that all means are different from one another nor does it indicate where the differences lie. To determine which plot means differ, the Tukey test a post-hoc evaluation technique was chosen. The Tukey test is one of the most widely accepted, and commonly used post-hoc tests which looks at multiple comparisons (Zar 1996).

6. Hypotheses Tested

Hypothesis 1: The first hypothesis tested the effect of site on white spruce annual total height at any given age. The one-way ANOVA model (height = site) was used to determine the effect of location on annual total height.

H_O = Mean annual total height does not differ between LOGS Site I and Site II at any age.

H_A = Mean annual total height does differ between LOGS Site I and Site II at any age.

Hypothesis 2: The second hypothesis analyzed the sites separately and tested the effect of espacement on annual total height at any given age. The one-way ANOVA model (height = space) was used to determine the effect of espacement on annual total height of white spruce.

H_O = Mean annual total height does not differ between any espacements on either LOGS site at any age.

H_A = Mean annual total height does differ between one or more espacements on either LOGS site at any age.

C. Results

Hypothesis 1: The first hypothesis tested whether mean annual total height of white spruce seedlings were affected by site at any given age. Table 3.1 and Figure 3.4 present the results from the ANOVA. The ANOVA indicated that after age 1, Site I had significantly less mean annual total height than Site II when all spacings and all replications were combined for each site (for F-values and degrees of freedom see

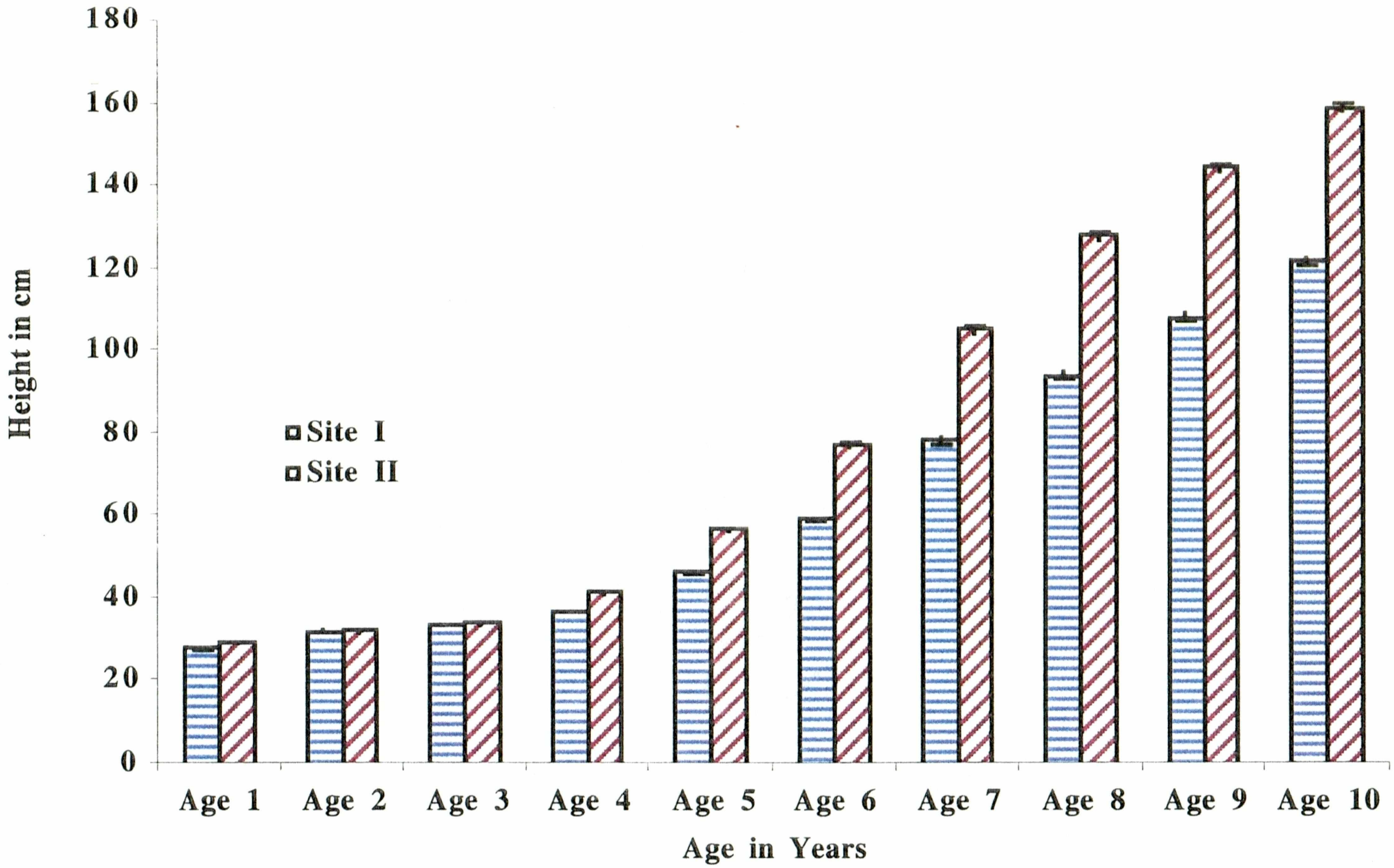

Figure 3.4. The effect of site on white spruce annual total height (cm) for the LOGS study from age 1 to age 10. Mean annual total heights at a given age, are presented with standard errors. Site I showed a significant decrease in annual total height as compared to Site II after age 1. All spacings and replications have been combined.

Appendix A). Site I mean annual total height ranged from 32.19 to 147.38 cm. Site II mean annual total height ranged from 32.26 to 188.56 cm.

Hypothesis 2: The second hypothesis analyzed the locations separately and tested whether espacement had an effect on white spruce annual total height at any given age. Tables 3.2 and 3.3 and Figures 3.5 and 3.6 present the results of the ANOVA. The ANOVA indicated significant differences in mean height and the Tukey test showed where the differences lay (for F-values and degrees of freedom see Appendix A).

For Site I, the Tukey test shows at ages 1, 2, 3, and 4 that there are consistently three groups, the spacings that fall into each group vary slightly from year to year. However, by age 5 and continuing through age 7 there are consistently two groupings (Table 3.2). At age 10 spacing 1 is significantly less than all the other spacings.

For Site II, the pattern is different. At ages 1 and 2 there are two distinct groupings, at age 3 three groupings, at ages 4 and 5 two groupings, at ages 6, 7, and 8 two distinct groupings, at age 9 no significant differences between spacings, and at age 10 two groupings (Table 3.3).

Table 3.1. The effect of site on white spruce annual total height (cm) for the LOGS study from age 1 to age 10. Mean heights at a given age, are presented with standard errors. All spacings and replications are combined.

	Age 1	**Age 2**	**Age 3**	**Age 4**	**Age 5**
Site I	32.19*	33.69	37.25	47.66	61.44
St. error	.2	.18	.2	.28	.42
Site II	32.26	34.61	42.48	58.72	79.83
St. error	.2	.19	.25	.38	.56
	Age 6	**Age 7**	**Age 8**	**Age 9**	**Age 10**
Site 1	80.09	96.71	111.19	125.23	147.38
St. error	.70	.78	.90	1.03	1.2
Site 2	106.71	129.48	146.03	160.89	188.56
St. error	.73	.86	.96	1.08	1.24

*Sites were not significantly different ($P \leq 0.05$)

Table 3.2. The effect of espacement on white spruce annual total height (cm) for the LOGS study at Site I. Mean heights and standard errors at each spacing are presented as well as the Tukey groupings to show which spacings were significantly different ($P \leq 0.05$). All replications are combined.

	Age 1	Age 2	Age 3	Age 4	Age 5
Space 1	32.45ab	33.70 b	37.08 bc	46.73 bc	59.52 b
St. error	.28	.27	.28	.40	.60
Space 2	32.09 b	33.84 b	37.86ab	49.65ab	65.61a
St. error	.45	.39	.43	.61	.91
Space 3	29.56 c	31.52 c	34.99 c	46.08 c	60.63 b
St. error	.58	.52	.58	.81	1.18
Space 4	34.50a	36.45a	39.94a	50.01a	63.13ab
St. error	.49	.45	.49	.78	1.31
Space 5	32.60ab	33.51 bc	37.14 bc	47.28abc	60.20 b
St. error	.60	.61	.74	1.11	1.64

	Age 6	Age 7	Age 8	Age 9	Age 10
Space 1	76.68 b	91.54 b	103.94 c	114.10 b	130.60 b
St. error	1.09	1.09	1.25	1.35	1.52
Space 2	87.07a	105.85a	121.89a	137.89a	163.66a
St. error	1.37	1.67	1.89	2.10	2.34
Space 3	80.70ab	99.49ab	116.56ab	135.40a	164.06a
St. error	1.66	2.16	2.58	3.05	3.54
Space 4	80.25ab	97.62ab	114.46ab	133.93a	163.42a
St. error	1.87	2.36	2.81	3.30	4.00
Space 5	79.20 b	95.56 b	110.84 bc	128.12a	154.34a
St. error	2.34	2.98	3.41	4.08	4.76

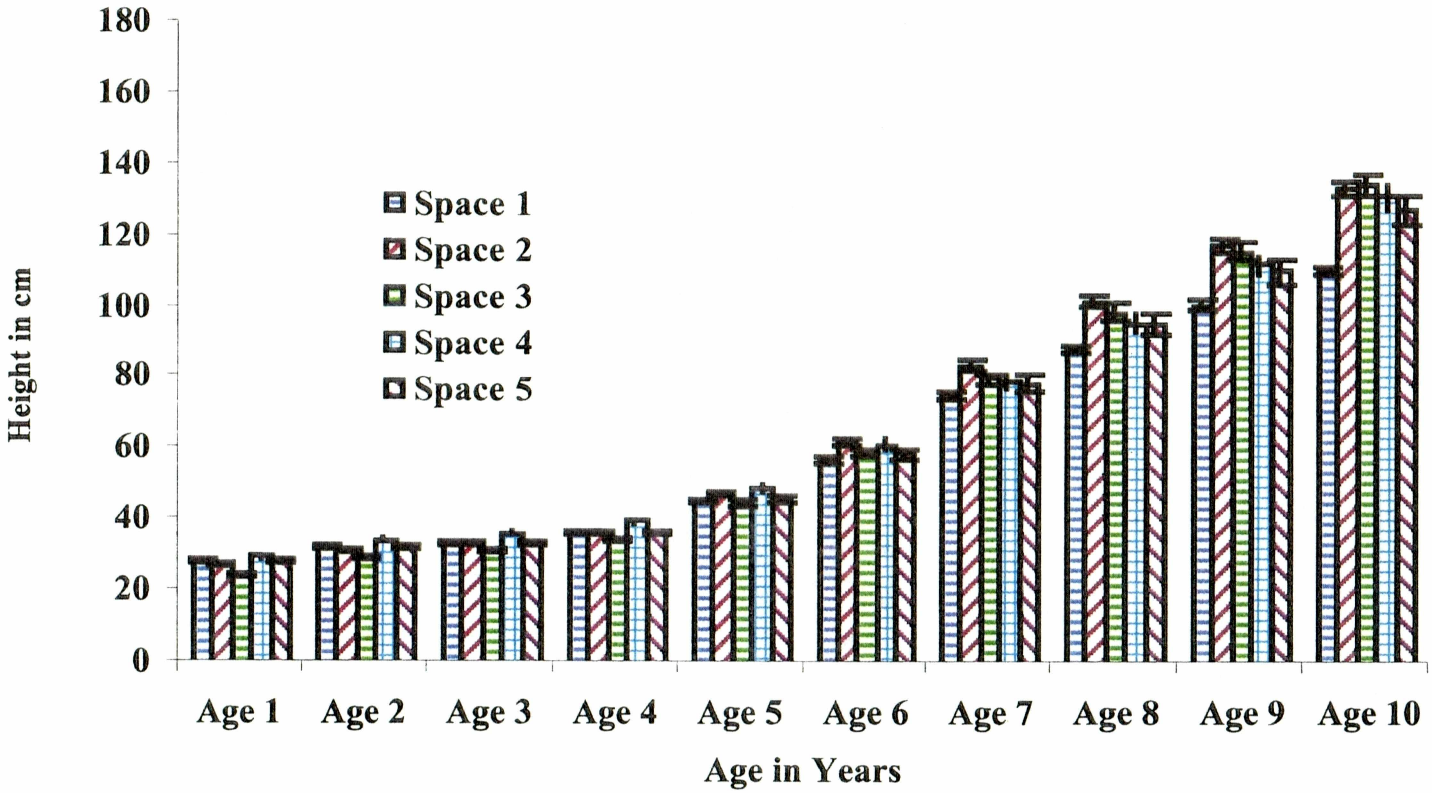

Figure 3.5. The effect of espacement on white spruce annual total height (cm) for the LOGS study for Site I. Mean heights and standard errors at each spacing are presented All replications were combined.

Table 3.3. The effect of espacement on white spruce annual total height (cm) for the LOGS study at Site II. Mean heights and standard errors at each spacing are presented as well as the Tukey groupings to show which spacings were significantly different (P≤0.05). All replications are combined.

	Age 1	Age 2	Age 3	Age 4	Age 5
Space 1	33.04a	35.46a	43.75a	60.26a	81.23a
St. error	.28	.26	.36	.54	.77
Space 2	33.73a	35.73a	42.45ab	58.38ab	80.54a
St. error	.39	.40	.49	.75	1.19
Space 3	29.41 b	31.76 b	40.39 bc	57.23ab	77.37ab
St. error	.62	.57	.77	1.16	1.69
Space 4	30.06 b	33.00 b	41.32abc	56.72ab	77.85ab
St. error	.59	.54	.72	1.12	1.70
Space 5	30.17 b	32.20 b	38.82 c	54.39 b	73.82 b
St. error	.70	.72	.97	1.45	2.20

	Age 6	Age 7	Age 8	Age 9	Age 10
Space 1	106.97ab	129.67ab	146.15ab	160.20ab	185.23ab
St. error	1.00	1.18	1.33	1.49	1.70
Space 2	108.35a	130.91a	147.07ab	161.99ab	191.07ab
St. error	1.60	1.86	2.04	2.24	2.53
Space 3	108.06a	131.27a	147.16ab	163.68ab	193.99ab
St. error	2.32	2.71	3.01	3.40	3.96
Space 4	106.25ab	130.15a	149.00a	165.33a	198.66a
St. error	2.17	2.66	3.06	3.60	4.33
Space 5	99.27 b	120.15 b	136.23 b	151.95 b	181.83 b
St. error	2.99	3.38	3.74	4.31	5.04

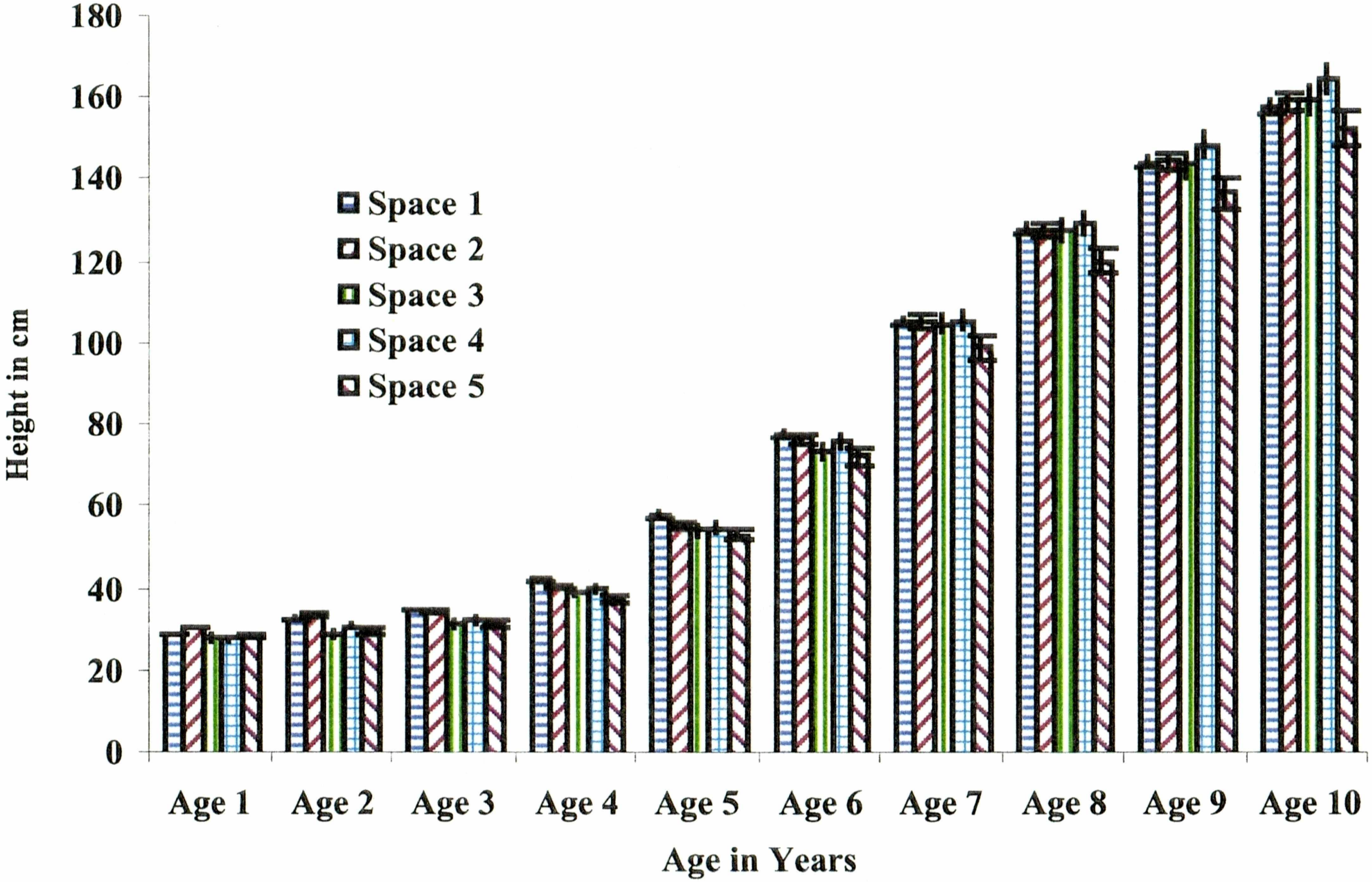

Figure 3.6. The effect of espacement on white spruce annual total height (cm) for the LOGS study for Site II. Mean annual total heights and standard errors at each spacing are presented. All replications were combined.

D. Discussion and Conclusions

Hypothesis 1: The first hypothesis tested whether there was an effect of site on mean annual total height of white spruce seedlings at any given age. Mean annual total height for all espacement plots and replications combined showed significant differences after age 1 that can be attributed to differences in site.

Annual total height of white spruce after regeneration is often affected by above ground competition and associated overstory shading (Eis 1980). In interior Alaska, fast growing species such as bluejoint reedgrass, alder, aspen and birch can overtop and shade white spruce seedlings and reduce their annual total height. From a management perspective, overstory shading should be avoided, but it is also important to not let seedlings be overexposed to direct sunlight and wind which would also decrease their chances of reaching maturity (Eis 1965). However, the reduced annual total height of Site I cannot be attributed to over-story shading because care was taken to regulary remove woody vegetation on these sites. One possible explanation is competition for moisture with other vegetation on the site.

The LOGS study sites are located within 1 km of each other but they are on different aspects. In interior Alaska aspect has been shown to greatly affect species composition of forest stands (Van Cleve et al. 1991). Site I is southerly and would have been dominated by naturally regenerating aspen whereas Site II is northeasterly and would have been dominated by naturally regenerating grass and scattered paper birch. This difference in species composition, points to the underlying differences of these sites. Aspect of the LOGS sites is most likely a high contributing factor in the observed differences in annual total height. There are many underlying ecosystem characteristics associated with differences in aspect, for example soil properties and solar radiation.

Associated with differences in aspect, one would expect to find differences in soil characteristics such as soil pH, soil moisture, soil nitrogen, and soil carbon (Ruess et al. 1996). These soil characteristics are directly linked to growth of white spruce (e.g., Van Cleve and Oliver 1983; Yarie et al. 1990), and, therefore, they would be expected to cause some of the significant differences in annual total height of white spruce observed at the two sites. Although soil samples were not taken for this study, soils have been evaluated at similar sites throughout interior Alaska, and show differences in soil characteristics on different aspects and sites (Troth et al. 1976).

Also associated with differences in aspect, are differences in incoming radiation. Another possible explanation for the decreased annual total height of white spruce at Site I is the larger amount of incident solar radiation received. Van Cleve et al. (1991) describe that southerly aspects have the highest amount of incoming radiation that contributes to drier and warmer soils; both of these factors have been associated with decreased white spruce seedling growth (Eis 1965).

These results indicate that although the two sites are within 1 km of each other, they can not be analyzed as one unit. Annual total height rates of white spruce seedlings are significantly different and this difference appears to be related primarily to the effect of aspect. These sites can however provide an estimate of the number of years for the seedlings to reach breast height (BH = 1.4 m), a good indicator of early performance. Using linear regression, the mean annual total height of each site for the first ten years provides an equation that can be used to calculate the age at which a seedling will reach BH. Using these regression models (Figure 3.7) Site I reached BH at 10.7 years during the 10^{th} growing season and Site II reached BH at 7.8 years during the 8^{th} growing season. The regression also provides a R^2 to assess how well the predicted line fits the observed data. The closer the R^2 value is to 1 the better the fit. For Site I the R^2 was 0.96 and for Site II the R^2 was 0.97. The average height for the first ten years of growth from both LOGS site can be found in Table 3.1. and Figure 3.4.

Hypothesis 2: The second hypothesis analyzed the sites separately and tested whether espacement had an effect on white spruce annual total height at any given age. The ANOVA (results provided in Appendix A) indicated that significant differences in mean annual total height existed between some espacements. Although many significant differences were found at early ages, as seedlings grew older, fewer significant differences were found among espacement plots.

An interesting pattern emerges from these data: As age of white spruce seedlings increases, height variability increases as well. For example, in the first years following planting the Tukey groupings of the spacing treatments were more distinct. By age 9 and 10, however, there is more overlap in the Tukey groupings of the spacing treatments. Thus, as the seedlings become older, it becomes more difficult to statistically detect differences in white spruce mean annual total height.

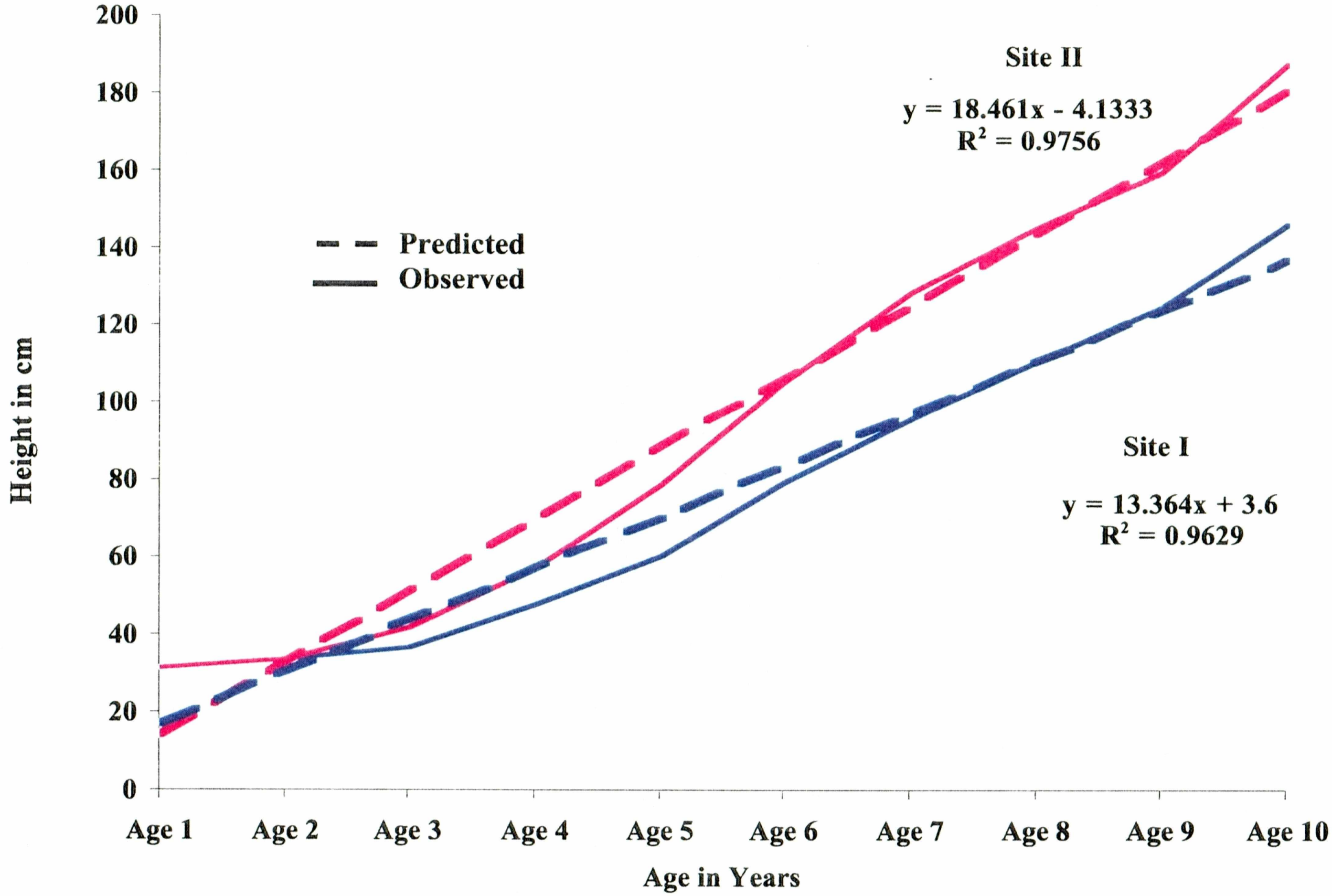

Figure 3.7. The observed mean annual total height (cm) of both LOGS sites with predicted linear regression lines and associated equations and the R^2 values for both sites.

Although statistically significant patterns in white spruce annual total height are difficult to detect, as the seedlings grow older, there are visual trends in annual total height at older ages that should not be ignored. These trends are consistently increasing through seedling development with annual total height greatest in spacings 2, 3,and 4, and least in spacings 1 and 5.

Spacing 1 (the narrowest) and Spacing 5 (the widest) exhibited the shortest heights at age 10 whereas spacings 2, 3, and 4 exhibited the tallest heights at age 10 (Figures 3.5 & 3.6). The annual total height patterns of white spruce described in this espacement study follow the trends of white spruce development from other espacement studies (e.g. Johnstone 1976; Pollack et al. 1992; Johnstone 1999). These studies found that middle spacings exhibited the tallest white spruce seedlings.

In conclusion, these results not only show the effects of espacement on white spruce annual total height, but also the importance of site quality. Proper espacement is a critical forest management decision. Espacement can affect future marketability, wood quality, and wood yield (Evert 1971). Site selection is of importance and needs to be taken into consideration when reforesting an area after harvesting or disturbance. Site location can affect annual total height through differences in belowground competition for nutrients and water, differences in solar radiance, and differences in soil characteristics.

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IV. PHASE TWO: OPERATIONAL PLANTATIONS

A. Introduction

Regeneration after timber harvest has long been recognized as one of the most expensive aspects of forest management as well as the single most important activity to insure a sustainable resource for future generations (McKinnon 1940). Without proper site preparation, white spruce can be a difficult species to reestablish by planting of seedlings. Direct seeding methods have proven to be even less effective (Youngblood and Zasada 1991).

Early growth of planted seedlings is often slow. Also, early height growth of white spruce is not as rapid as its hardwood associates and thus, often competes with other vegetation early in its life cycle. In addition to being a slow growing species, planted white spruce seedlings often exhibit signs of planting check which can be detected by either slower than normal height growth, reduced needle size, or needle discoloration (Mullin 1963). Planting check results from improper planting depth, damage to roots during planting, limitation of adequate nutrient supply, excess or deficient moisture, competition with other plants, or low temperatures (Brace 1964; Eis 1965; Dobbs 1976; Binder and Fielder 1988; Nienstaedt and Zasada 1990). These situations can occur as a result of poor economic conditions that limit the possibility for appropriate harvest practices, poor planting practices, or site preparation. White spruce

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Hollingsworth, J. (prepared for submission to Canadian Journal of Forestry Research) Assessing impacts of site on early growth rates of planted white spruce in interior Alaska.

has an advantage later in its life cycle because it is shade tolerant and is able to eventually overtake or replace competing vegetation on good sites due to its long life span (Nienstaedt and Zasada 1990). Therefore, the ability to predict height growth or the knowledge of height growth patterns is of much interest to forest managers in interior Alaska.

In addition to annual seedling heights, site variables known to affect height growth were collected at operational plantations in an attempt to identify causes of annual total height variations. The ability to understand how key environmental variables (slope, aspect, soil moisture, and above ground competition) affect the height growth of seedlings is an important step towards predicting performance of white spruce plantations. These variables were chosen based on relative ease of collection and importance. This knowledge will increase the ability of forest managers to achieve management objectives.

The objectives of this research were 1) to determine annual total height patterns of operational plantations around the Fairbanks area, 2) to compare these growth patterns to the LOGS experimental plantations, and 3) to determine environmental factors responsible for annual total height differences.

B. Methods

1. Plantation selection

White spruce annual total height data were collected from 18 plantations on Tanana Valley State Forest lands surrounding Fairbanks, Alaska (Figure 4.1). Plantations

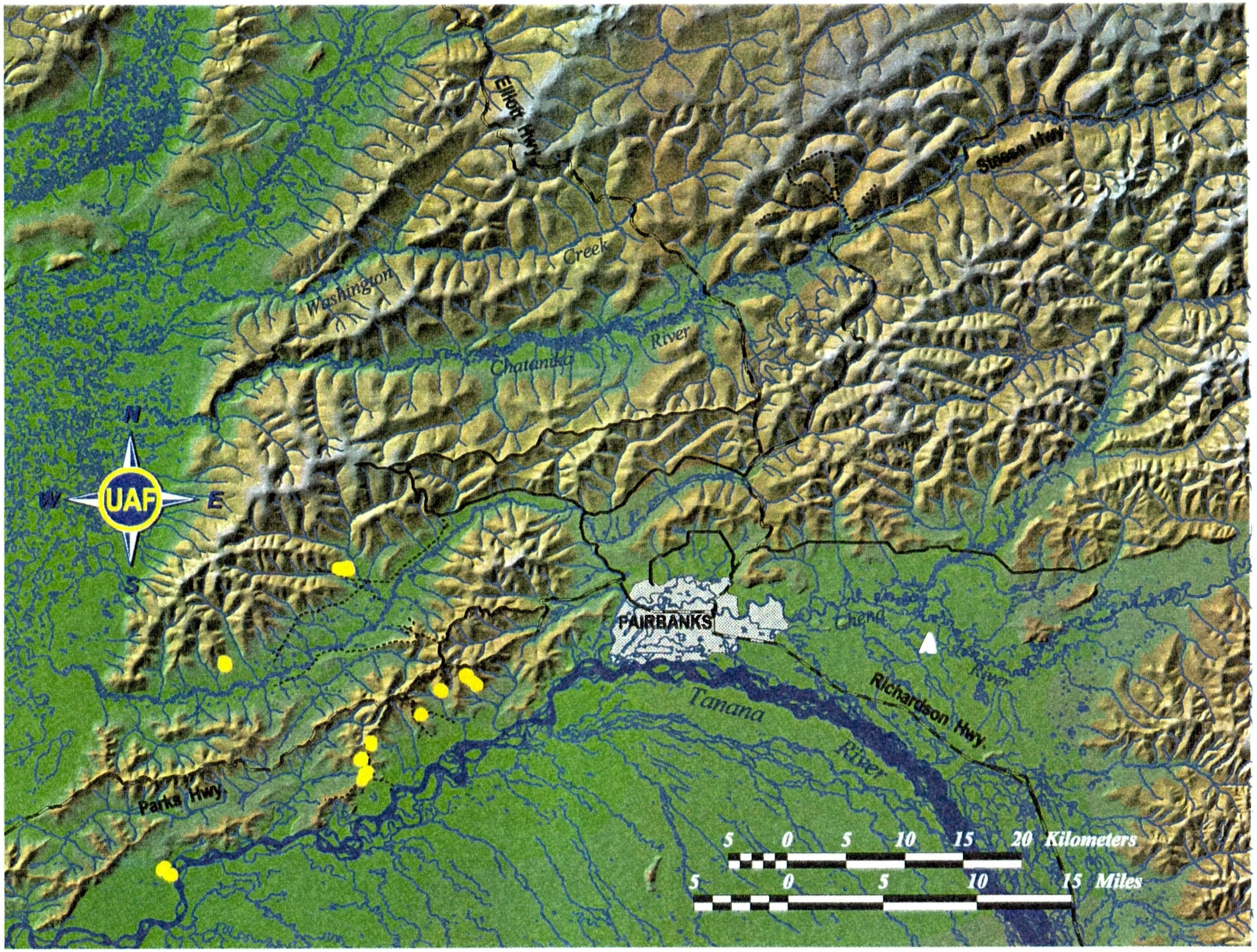

Figure 4.1. Locations of 18 white spruce plantations near Fairbanks Alaska that were assessed for height growth and a suite of environmental variables in July 1998.

were selected because of their proximity to Fairbanks, accessibility, and availability of a complete record of regeneration activities available from the Alaska Department of Natural Resources Division of Forestry. Establishment year varies among plantations; the youngest was planted in 1994 and the oldest was planted in 1986.

2. Plot Establishment and Measurements

Power analysis, is a statistical tool, used to determine minimum sample size required to estimate the difference between population means with a confidence interval of a specified width (Zar 1996). Annual total height from the Levels-of-Growing-Stock plantations was used for the power analysis to determine the number of trees as well as the number of plots needed at each operational plantation. Based on the power analysis for sample size determination, and estimating the difference between more than two population means, six temporary plots of 25 planted seedlings were randomly selected in each plantation. Plots were randomly dispersed throughout each plantation. The area (ha) of each plantation varied. A random number table was used to estimate the distance from plot to plot in order to achieve complete coverage of each plantation (i.e., for large plantations, larger distances between plots and for small plantations, smaller distances between plots). Once the center of the temporary plot was established the closest 25 planted trees to the center were then measured. Plot size varied due to survival of planted seedlings. Only 16 of the 18 plantations visited had adequate stocking for height growth measurements to be taken; hence, plantations 3 and 4 were excluded from any analyses.

Total height was measured during late July after seasonal height growth had stopped. Total height and internode heights (to obtain past annual height) above ground were measured to the nearest centimeter using a 1 cm graduated measuring rod. Environmental variables collected at each plot were percent slope, aspect (N, S, E, or W), slope-position (upland, mid-slope, or lowland), aboveground competition class (slight, moderate, heavy, or extreme) and soil moisture regime (poorly drained, moderately drained, or well drained).

3. Statistical Analyses

All statistical analyses were completed using SAS version 6.1. The SAS General Linear Model (GLM) was selected as the appropriate approach. The GLM procedure for Analysis of Variance (ANOVA) is especially useful with unbalanced data sets (SAS 1985). ANOVA is a single test for comparing multiple means. Major assumptions of ANOVA are (i) data are normally distributed, (ii) variances within the data are equal, and (iii) samples are independent of each other. The data were tested using the SAS univariate procedure; data met two of the three assumptions of ANOVA. The data were found to be normally distributed and have equal variances; however, because annual height growth is not independent of year (i.e., height of white spruce increases as seedlings get older), data were analyzed separately by year. Plantation was chosen as the experimental unit because variability was much larger within plots than due to plots.

Although ANOVA tests to see whether significant differences occur among the plantation means, it does not imply that all means are different from one another nor does it show where the differences lie. Post-hoc evaluation was used to determine which plantation means differ. The Tukey test, which was used, is one of the most widely accepted and commonly used post-hoc tests that looks at multiple comparisons (Zar 1996).

Height growth is a discrete event that occurs annually. The attempt here is not to monitor how the environmental variables affect height growth annually but how they have effected seedling development. The operational plantations where visited only once, and since operational plantations were of different ages, a new variable called growth rate was needed to be formed to eliminate the effect of age. Growth rate was calculated using the slope (increase in height over time) of each tree that was measured.

Determining the degree of influence of each environmental variable is complex due to the potential interdependent nature of the variables. For example, competition and soil moisture, two of the environmental variables collected, are dependent on other variables such as aspect or slope position. Therefore, they cannot be analyzed using simple multiple regression. Multiple regression looks at the effects of a single dependent variable and does not consider the effects of multiple dependent variables on one another (Walker et al. 1995; Carroll et al. 2001; Mitchell 1993).

Since there are multiple variables to consider in this data set in order to determine the degree of influence each environmental variable has on the growth rate of white spruce, path analysis was chosen as the appropriate multivariate technique. Path analysis partitions variation from observational data into causal or direct and non-causal or indirect effects based on a specific hypothesis. The associated path diagram conceptually describes the hypothesis and how the variables can affect one another (Carroll et al. 2000; Li 1975). Path analysis is a more general form of multiple regression that allows consideration of complicated causal relationships with more than one dependent variable and the effects of dependent variables on one another (Walker et al. 1995; Mitchell 1993). Path analysis can be used to compare multiple causal models to determine the most significant causal relationships. This study, however, is interested in the conceptual path diagram and associated correlations between each variable and the associated regression coefficients and does not test the validity of multiple models.

The multiple variables examined in this study were growth rate, competition, and soil moisture (i.e., the variables measured that are dependent on abiotic factors) and percent slope, aspect, and slope position (i.e., the variables measured that are independent of abiotic factors). The conceptual path diagram used (Figure 4.2) shows the hypothetical causal relationships of the dependent and independent variables. Variables that can affect growth rate directly include competition, percent slope, aspect, slope position, and soil moisture. Variables that affect competition directly include percent slope, aspect, slope position, and soil moisture. Variables that affect soil moisture directly include percent slope, aspect, and slope position.

To analyze this path diagram, standardized regression coefficients (direct effects) were calculated using the SAS procedure for regression. Path coefficients are standardized regression coefficients. They indicate the number of standard deviations of change in the dependent variable expected from a unit change in the independent variable with any other effect of other independent variables held constant (Mitchell 1993). The total unexplained variance for each dependent variable (U) was calculated using the total

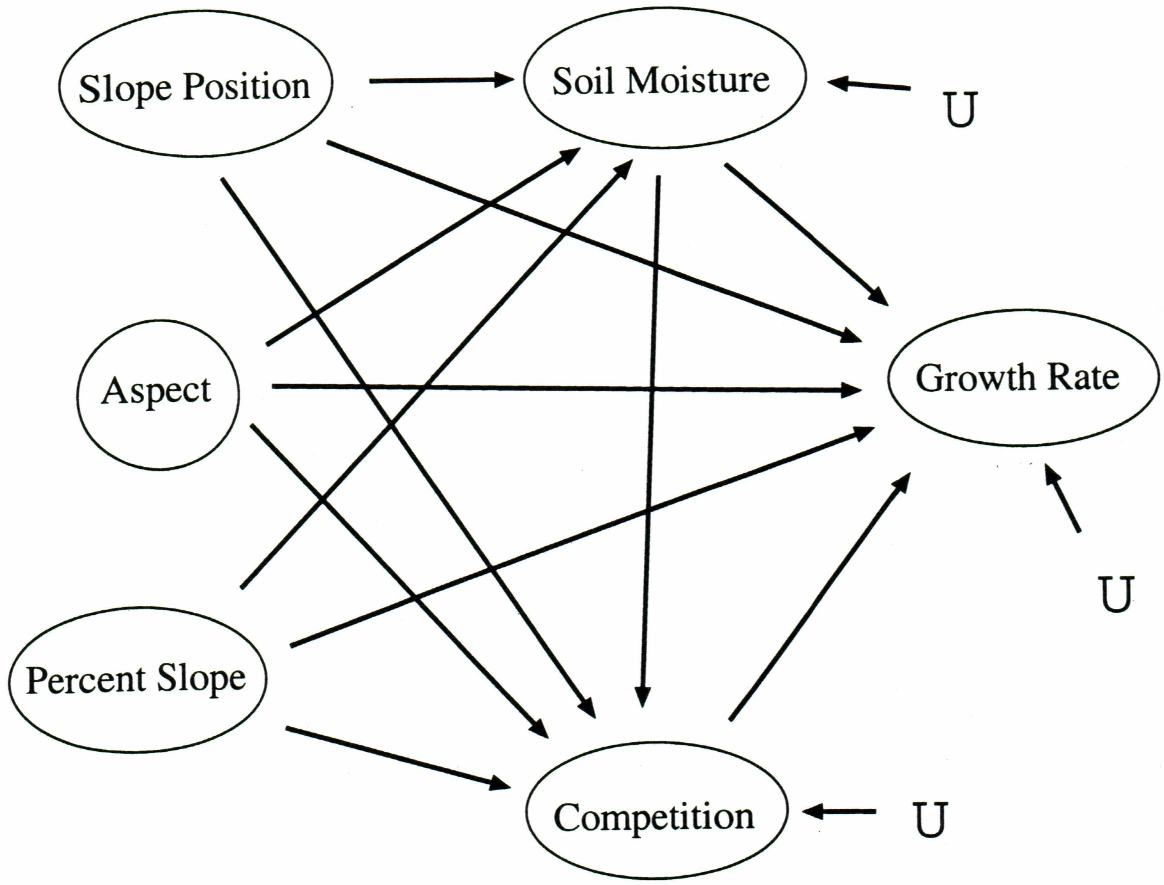

Figure 4.2. Hypothesized path diagram for the environmental effects on model for growth rate of planted white spruce seedlings. These paths were assumed to be typical relationships found in boreal forests. **U** = the amount of variance unexplained by this model, for example, any variable that could affect height growth that was not measured.

explained variance (R^2) where ($U = \sqrt{1-R^2}$). The SAS procedure CALIS calculated the indirect and total effects of the model for the path diagram.

4. Hypotheses tested

Hypothesis 1: The first hypothesis tested whether white spruce height growth at any given age was significantly different among operational plantations. The one-way ANOVA model (height = plantation) was used to determine if differences existed.

H_O = Mean height growth does not differ among plantations at any age.

H_A = Mean height growth does differ among plantations at any age.

Hypothesis 2: The second hypothesis tested whether white spruce height growth at any given age was significantly different between either of the LOGS experimental plantations and the operational plantations. The one-way ANOVA model (height = locations) was used to determine if differences existed.

H_O = Mean height growth does not differ among locations at any age.

H_A = Mean height growth does differ among locations at any age.

Hypothesis 3: The third hypothesis tested the degree of influence of selected environmental variables on height growth rate of white spruce seedlings throughout the Fairbanks area. The path diagram (Figure 4.2) conceptually shows the hypothetical contribution of the direct and indirect effects of the environmental variables on height growth.

H_O = All environmental variables contribute equally to the variability in growth rate across all the plantations.

H_A = Environmental variables contribute different amounts to the variability in growth rate across all the plantations.

C. Results

Hypothesis 1: The first hypothesis tested whether white spruce annual total height was significantly different among operational plantations. Mean annual total height values can be found in Table 4.1. The ANOVA indicated significant differences in mean annual total height between some plantations (for F-values and degrees of freedom see Appendix B).

At age 1, mean annual total height for the 16 plantations ranged from 13.27 cm (Plantation 11) to 28.25 cm (Plantation 9). At age 5, mean annual total height ranged from 46.78 cm (Plantation 11) to 78.85 cm (Plantation 8). At age 10, mean annual total height for three plantations ranged from 157.57 cm (Plantation 13) to 199.83 cm (Plantation 12).

At age 1, there were seven Tukey groupings, and these remained until age 3 with only a slight change in composition of the groupings (Table 4.1). After age 5 the four plantations established in 1993 (and were five years old) dropped out of the analysis causing a decrease in sample size. At age 7, only seven plantations remained with four distinct Tukey groupings; by age 9, only three plantations could be analyzed resulting in two distinct Tukey groupings; plantation 13 (134.6 cm) was significantly shorter than either plantation 9 (163.1 cm) or plantation 12 (164.9 cm) (Table 4.1 and Figure 4.3).

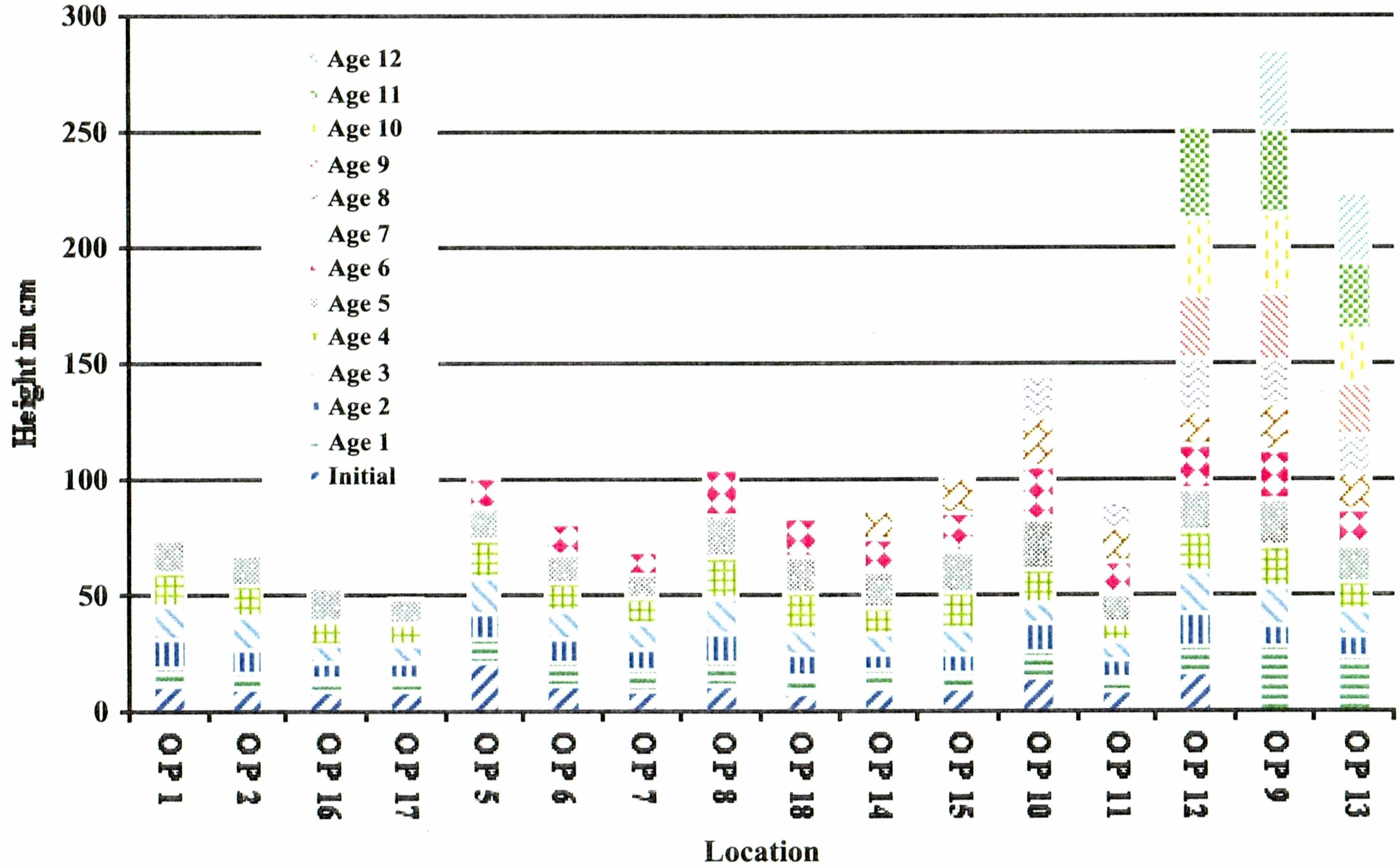

Figure 4.3. Mean annual total height (cm) of all plots combined on each operational plantation within the Fairbanks area. Plantations are grouped by age. Standard error bars have been eliminated because they would overlap too much to present graphically

Table 4.1. Mean annual total height (cm) and standard errors of all plots combined on each operational plantation within the Fairbanks area. Tukey test groupings are used to show which plantations were significantly different ($P \leq 0.05$). Plantations are grouped by age starting with the initial height when planted.

	Initial	Age 1	Age 2	Age 3	Age 4	Age 5
Plantation 1	11.09 cd	18.56 cdef	27.11 bcd	45.91ab	59.84abcd	74.55abc
St. error	0.28	0.26	0.27	0.38	0.56	1.03
Plantation 2	10.32 cde	17.38 defg	27.11 de	41.11abc	54.72 cde	68.20 bcd
St. error	0.25	0.24	0.19	0.45	0.65	0.71
Plantation 16	9.13 de	14.63 gh	20.63 fgh	28.35 h	38.49 fg	52.18 fg
St. error	0.42	0.51	0.55	0.53	0.59	0.64
Plantation 17	8.83 de	14.27 gh	20.18 gh	27.72 h	36.84 fg	47.88 fg
St. error	0.31	0.28	0.31	0.37	0.52	0.59
Plantation 5	21.16 bc	21.03 bc	31.45abc	46.08a	63.02a	76.08ab
St. error	0.43	0.44	0.52	0.67	0.74	0.71
Plantation 6	10.58 cde	19.06 cd	28.62 cd	40.53 bcd	53.06 de	64.66 de
St. error	0.30	0.36	0.44	0.64	0.59	0.95
Plantation 7	9.23 de	17.03 defg	23.91 efg	30.62 fgh	41.78 f	51.61 fg
St. error	0.19	0.20	0.33	0.43	0.69	0.70
Plantation 8	10.59 cde	17.19 defg	28.72 cd	44.26ab	61.77abc	78.85a
St. error	0.13	0.48	0.46	0.54	0.70	0.91
Plantation 18	8.42 e	15.47 fgh	23.31 efg	34.95 efg	49.71 e	65.91 cd
St. error	0.28	0.37	0.46	0.41	0.72	0.68
Plantation 14	9.97 cde	15.52 efgh	21.87 fgh	29.60 gh	41.34 fg	56.54 ef
St. error	0.26	0.23	0.37	0.32	0.45	0.97
Plantation 15	10.27 cde	16.42 defgh	24.52 ef	35.52 def	50.45 e	68.18 bcd
St. error	0.27	0.28	0.42	0.43	0.44	0.76
Plantation 10	14.11 b	18.74 cde	29.36 bcd	41.19abc	55.42 bcde	76.41ab
St. error	0.19	0.35	0.40	0.66	0.71	0.92
Plantation 11	8.89 de	13.27 h	19.03 h	26.47 h	34.41 g	46.78 g
St. error	0.12	0.21	.040	0.71	0.80	0.87
Plantation 12	16.74a	24.06 ab	32.69ab	45.39ab	61.48ab	79.14a
St. error	0.23	0.30	0.37	0.60	0.66	0.91
Plantation 9	---	28.25a	34.88a	45.05ab	60.09abc	76.72ab
St. error		0.24.	0.27	0.33	0.67	1.06
Plantation 13	---	23.21 b	30.23 bcd	36.69 cde	49.37 e	64.55 de
St. error		0.19	0.32	0.43	0.51	0.85

(Table 4.1 Continued)

	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age12
Plantation 1							
Plantation 2							
Plantation 16							
Plantation 17							
Plantation 5	89.41a						
St. error	1.26						
Plantation 6	77.36 cd						
St. error	1.14						
Plantation 7	61.91 e						
St. error	0.86						
Plantation 8	98.70a						
St. error	2.17						
Plantation 18	81.66 bcd						
St. error	1.31						
Plantation 14	71.68 de	83.32 cd					
St. error	1.19	2.23					
Plantation 15	84.79 bc	100.17 b					
St. error	0.97	1.57					
Plantation 10	99.95a	121.29a	139.34a				
St. error	1.44	2.61	3.75				
Plantation 11	61.51 e	75.17 d	86.11 c				
St. error	1.51	1.94	2.37				
Plantation 12	97.61a	112.77a	136.27a	164.93a	199.83a	236.41a	
St. error	2.14	3.55	3.98	4.68	6.01	6.23	
Plantation 9	97.66a	117.04a	135.77a	163.13a	195.92a	235.87a	268.09a
St. error	1.63	2.46	3.53	4.39	5.32	5.79	6.47
Plantation 13	79.88 bcd	94.61 bc	112.41 b	134.62 b	157.57 b	187.02 b	217.04 b
St. error	0.97	1.28	2.12	3.27	4.07	4.51	5.17

Hypothesis 2: The second hypothesis tested whether white spruce annual total height was significantly different between either of the LOGS experimental plantations and the operational plantations. The ANOVA indicated that there were significant differences in mean annual total height between some locations (for F-values and degrees of freedom see Appendix B).

At age 1, mean annual total height ranged from 13.27 cm (Plantation 11) to 29.65 cm (LOGS Site II). At age 5, mean annual total height ranged from 46.78 cm (Plantation 11) to 79.14 cm (Plantation 12). At age 10, mean annual total height ranged from 164.06 cm (LOGS Site I) to 199.83 cm (Plantation 12).

Including the two LOGS experimental sites, at age 1, for 18 plantations (16 operational and two LOGS) six Tukey groupings were found in which LOGS Site I, LOGS Site II, and Plantation 9 were significantly taller than the rest of the plantations (Table 4.2). For ages 2-5 Tukey groupings ranged from seven to nine and varied from year to year with only a slight pattern developing. The LOGS Site II (31.76 cm - 77.86 cm) was always in the tallest groupings; however Site I (31.5 cm-60.6 cm) was no longer significantly taller than the majority of the operational plantation (Table 4.2 and Figure 4.4). By age 7 there were four distinct Tukey groups, with Site II (131.2 cm) and Plantation 10 significantly taller than most of the operational plantations and Site I (99.4 cm) not significantly taller than most of the operational plantations. At age 9 with five plantations remaining there were two distinct Tukey groupings; Plantation 12 (164.9 cm), Site II (163.6 cm), and Plantation 9 (163.1 cm) were significantly taller than Site I (135.4 cm) and Plantation 13 (134.6 cm).

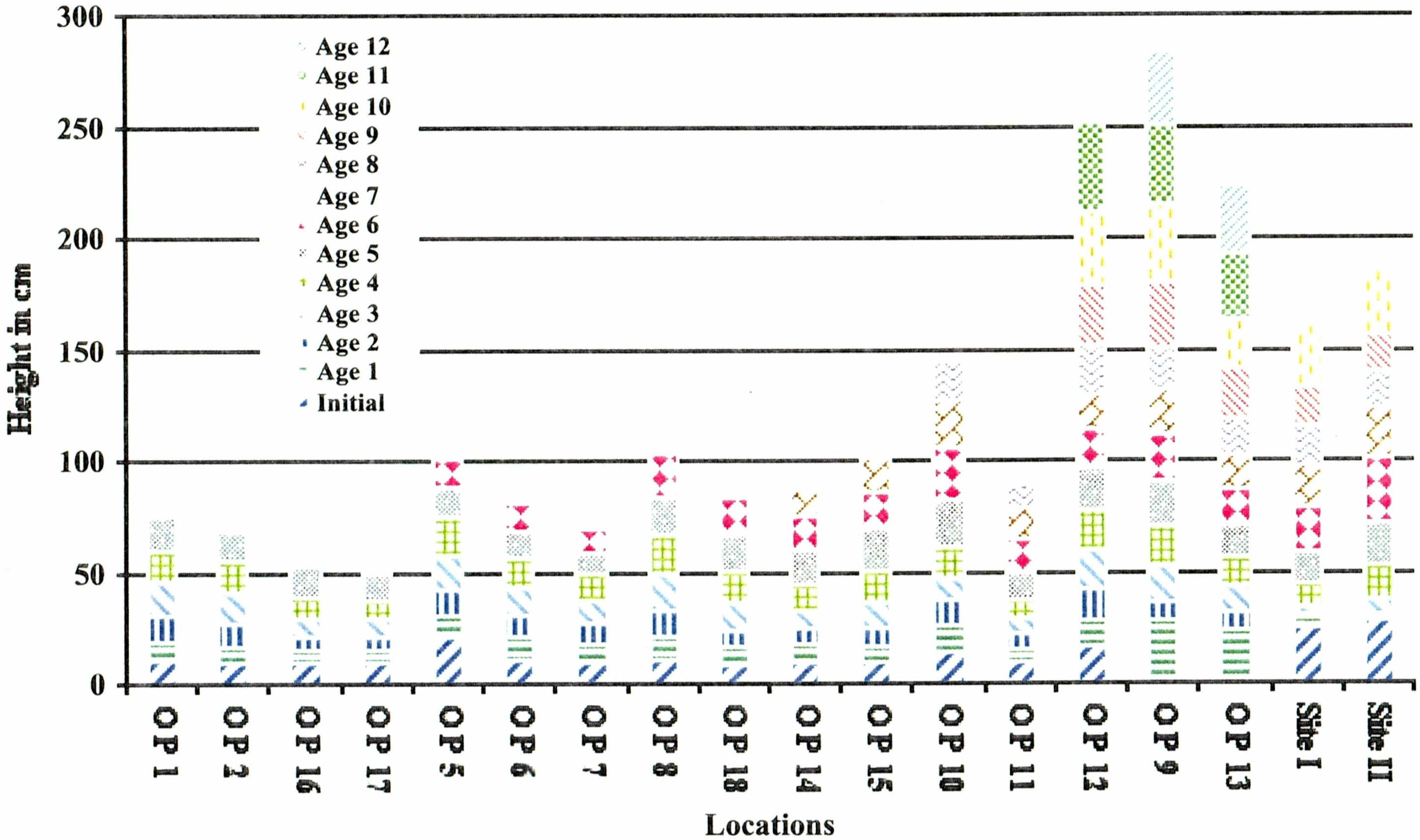

Figure 4.4. Mean annual total height (cm) of all plots combined on each operational plantation within the Fairbanks area with LOGS sites for comparison. Plantations are grouped by age. Standard error bars have been eliminated because the overlap makes it difficult to interpret mean growth heights.

Table 4.2. Mean annual total height (cm) and standard errors of all plots combined on each operational plantation within the Fairbanks area including LOGS experimental plantations for comparison. Tukey test groupings are used to show which plantations were significantly different ($P \leq 0.05$). Plantations are grouped by age starting with the initial height.

	Initial	**Age 1**	**Age 2**	**Age 3**	**Age 4**	**Age 5**
Plantation 1	11.09 ef	18.56 cde	27.11 bcd	45.91a	59.84abcd	74.55abc
Plantation 2	10.32 ef	17.38 def	27.11 de	41.11abc	54.72 cdef	68.20 bcd
Plantation 16	9.13 ef	14.63 fg	20.63 gh	28.35 g	38.49 ij	52.18 fgh
Plantation 17	8.83 f	14.27 fg	20.18 gh	27.72 g	36.84 ij	47.88 gh
Plantation 5	21.16 de	21.03 bc	31.45abc	46.08a	63.02a	76.08ab
Plantation 6	10.58 ef	19.06 cd	28.62 cd	40.53 bcd	53.06 def	64.66 de
Plantation 7	9.23 ef	17.03 def	23.91 efg	30.62 fg	41.78 hi	51.61 gh
Plantation 8	10.59 ef	17.19 def	28.72 cd	44.26ab	61.77ab	78.85a
Plantation 18	8.42 f	15.47 efg	23.31 efg	34.95 ef	49.71 fg	65.91 cd
Plantation 14	9.97 ef	15.52 efg	21.87 fgh	29.60 g	41.34 hij	56.54 efg
Plantation 15	10.27 ef	16.42 defg	24.52 ef	35.52 def	50.45 efg	68.18 bcd
Plantation 10	14.11 cd	18.74 cde	29.36 bcd	41.19abc	55.42 bcdef	76.41ab
Plantation 11	8.89 f	13.27 g	19.03 h	26.47 g	34.41 j	46.78 h
Site I	28.31a	29.56a	31.52abc	34.99 ef	46.07 gh	60.62 def
St. error	0.16	0.20	0.18	0.20	0.28	0.48
Site II	24.94 b	29.41a	31.76abc	40.38 bcd	57.25abcde	77.86a
St. error	0.17	0.20	0.19	0.25	0.38	.56
Plantation 12	16.74 c	24.06 b	32.69ab	45.39ab	61.48ab	79.14a
Plantation 9	---	28.25a	34.88a	45.05ab	60.09abc	76.72ab
Plantation 13	---	23.21 b	30.23 bcd	36.69 cde	49.37 fg	64.55 de

(Table 4.2. Continued)

	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age12
Plantation 1							
Plantation 2							
Plantation 16							
Plantation 17							
Plantation 5	89.41 bc						
Plantation 6	77.36 de						
Plantation 7	61.91 f						
Plantation 8	98.70ab						
Plantation 18	81.66 cde						
Plantation 14	71.68 ef	83.32 de					
Plantation 15	84.79 cd	100.17 c					
Plantation 10	99.95ab	121.29ab	139.34a				
Plantation 11	61.51 f	75.17 e	86.11 c				
Site I	80.70 cde	99.48 c	116.55 b	135.40 b	164.06 b		
St error	1.70	1.78	1.90	1.03	1.20		
Site II	108.06a	131.27a	147.16a	163.68a	193.98a		
St error	0.73	0.86	0.96	1.08	1.24		
Plantation 12	97.61ab	112.77 b	136.27a	164.93a	199.83a	236.41a	
Plantation 9	97.66ab	117.04 b	135.77a	163.13a	195.92a	235.87a	268.09a
Plantation 13	79.88 cde	94.61 cd	112.41 b	134.62 b	157.57 b	187.02 b	217.04 b

Hypothesis 3: The third hypothesis tested which environmental variables contributed the most to differences in growth rate of white spruce seedlings. The regression results shown in Table 4.3 indicate which variables where significant for each of the regressions. Competition, slope position, and percent slope had a significant effect on growth rate but soil moisture and aspect did not. Soil moisture, slope position, percent slope, and aspect had significant effects on competition. Percent slope and aspect had significant effects on soil moisture but slope position did not. Figure 4.5 is a graphical display of the regression results.

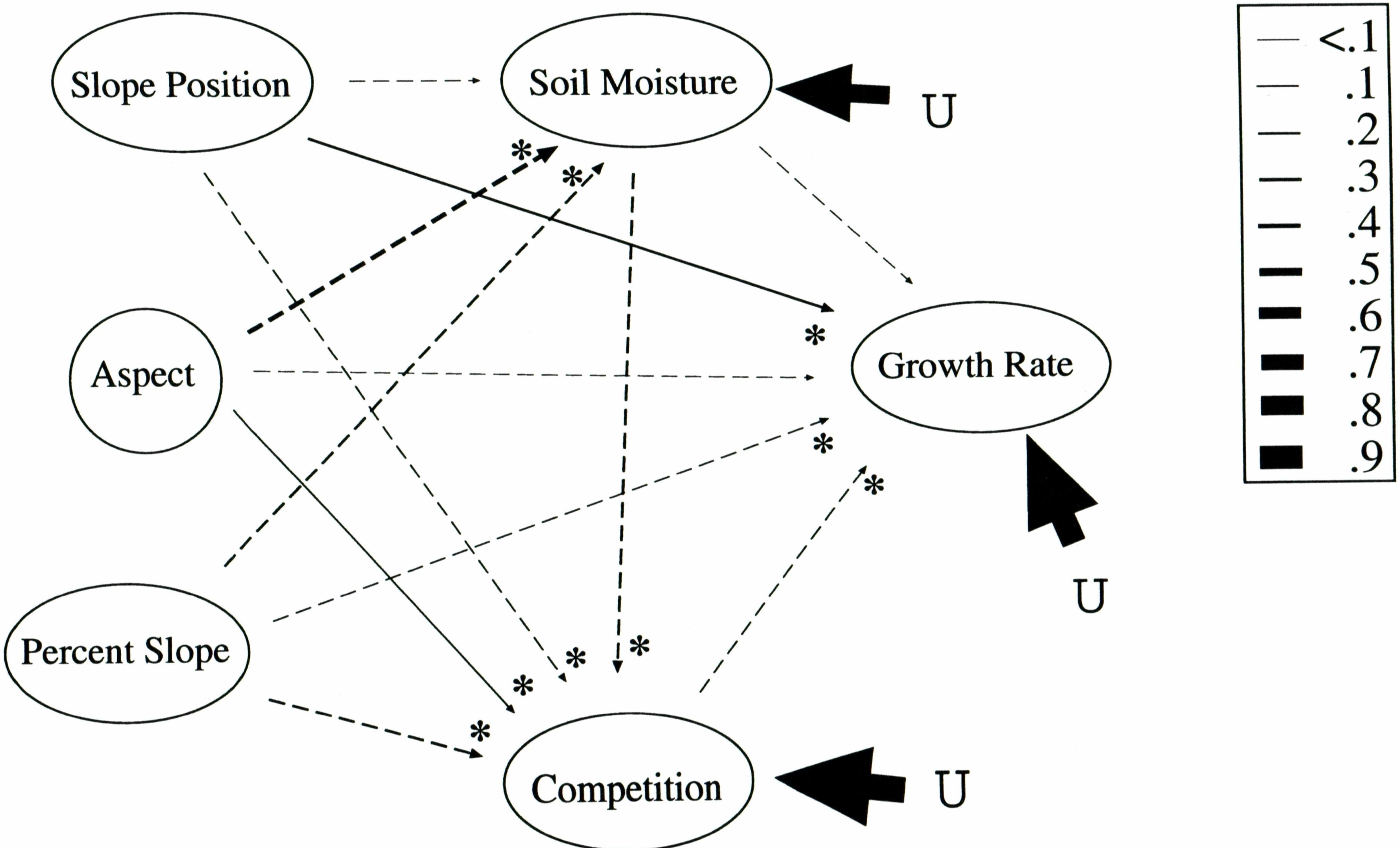

Figure 4.5 Solved path diagram for growth rate of planted white spruce seedlings. Arrows show direct effects, solid lines are positive and dashed lines are negative. Line width is proportional to strength of relationship. Actual values for path coefficients are in Table 4.3.
* Significant direct effects (P≤0.05)

Table 4.3 Direct, indirect, and total effects for the path model of the relationship between growth rate of planted white spruce seedlings and measured environmental variables.

Variable	Growth Rate			Competition			Soil Moisture		
	DE	IE	TE	DE	IE	TE	DE	IE	TE
Competition	- 0.17	--	- 0.18	--	--	--	--	--	--
Soil Moisture	--	0.02	0.10	- 0.23*	--	- 0.12	--	--	--
Slope Position	0.22	0.01	0.22	- 0.13*	0.02	- 0.10	- 0.05	--	- 0.14
% Slope	- 0.19	- 0.01	- 0.14	- 0.25*	0.06	- 0.15	- 0.44*	--	- 0.51
Aspect	- 0.03	- 0.05	- 0.10	0.14*	0.04	0.15	- 0.21*	--	- 0.29
R^2 (U)[1]	0.11 (0.94)			0.10 (0.95)			0.29 (0.84)		

Direct effects are standardized regression coefficients, DE, direct effect; IE indirect effects; TE total effects.
* Significant direct effects (P≤0.05). U[1] = Total unexplained variance.

D. Discussion and Conclusions

Hypothesis 1: The first hypothesis tested whether white spruce annual total height was significantly different among operational plantations. Mean annual total height for all plots combined showed significant differences at all ages that can be attributed to differences among the plantations.

Total annual height differences among operational plantations were not unexpected. The operational plantations were planted over a seven-year period, 1986 - 1993. They were planted on a variety of slopes, aspects, slope positions, and growing with differing degrees of above-ground competition. Planting specifications also varied among plantations. Seedling container types varied, planting occurred at different times during the growing season, and seedlings came from several different nurseries. Site preparation also differed between sites. These factors are known to contribute to both long-term and short-term white spruce height growth (Stiell 1976).

Hypothesis 2: The second hypothesis tested whether there were significant differences between either of the LOGS experimental plantations and the operational plantations on white spruce annual total height at any given age. After age 3, there were significant differences in mean annual total height between each of the LOGS sites and operational plantations. The significant differences in the initial height and height at age 1 between the LOGS plantations and operational plantations can be attributed to age and condition of seedlings when planted (T. Malone, personal communication). Seedlings planted in the LOGS plantations were one year old and seedlings planted in the operational plantations were less than six months old. This could potentially explain the differences in initial total height and total height at age 1. Essentially, seedlings at the LOGS sites were taller when planted. The seedlings planted operationally were initially shorter yet they exhibited a faster growth rate than the LOGS seedlings. The reason for the period of reduced height growth at the LOGS experimental plantations was most likely due to the seedling roots being root bound in the container in which they were grown. Figure 4.6 shows how both LOGS sites compare to operational plantation established the same year. Site I reached breast height (BH) at 10.7 years during the 10th growing season and Site II reached BH at 7.8 years during the 8th growing season Figure 3.7. Interestingly, operational plantations reached breast height during the same range of growing seasons between the 8th and the 10th.

Hypothesis 3: The third hypothesis tested which environmental variables contributed the most to differences in height growth rate of white spruce seedlings. A path diagram was developed to describe the causal effects of the environmental variables. The regression model for growth rate = competition + slope position + aspect +percent slope + soil moisture +Unknown was significant. However, soil moisture and aspect did not contribute significantly to the regression (Table 4.3). Slope position had the highest path coefficient, indicating that seedlings planted on upland sites have better height growth rates than seedlings planted on lowland sites. In contrast, Van Cleve et al. (1983) found no significant difference between upland and lowland mature white spruce stands in aboveground net primary production. These contrasting results may likely be due to difference in the ages of the stands in question. This suggests that early in the growth of white spruce, topographic position is very important, however, as the stand matures other

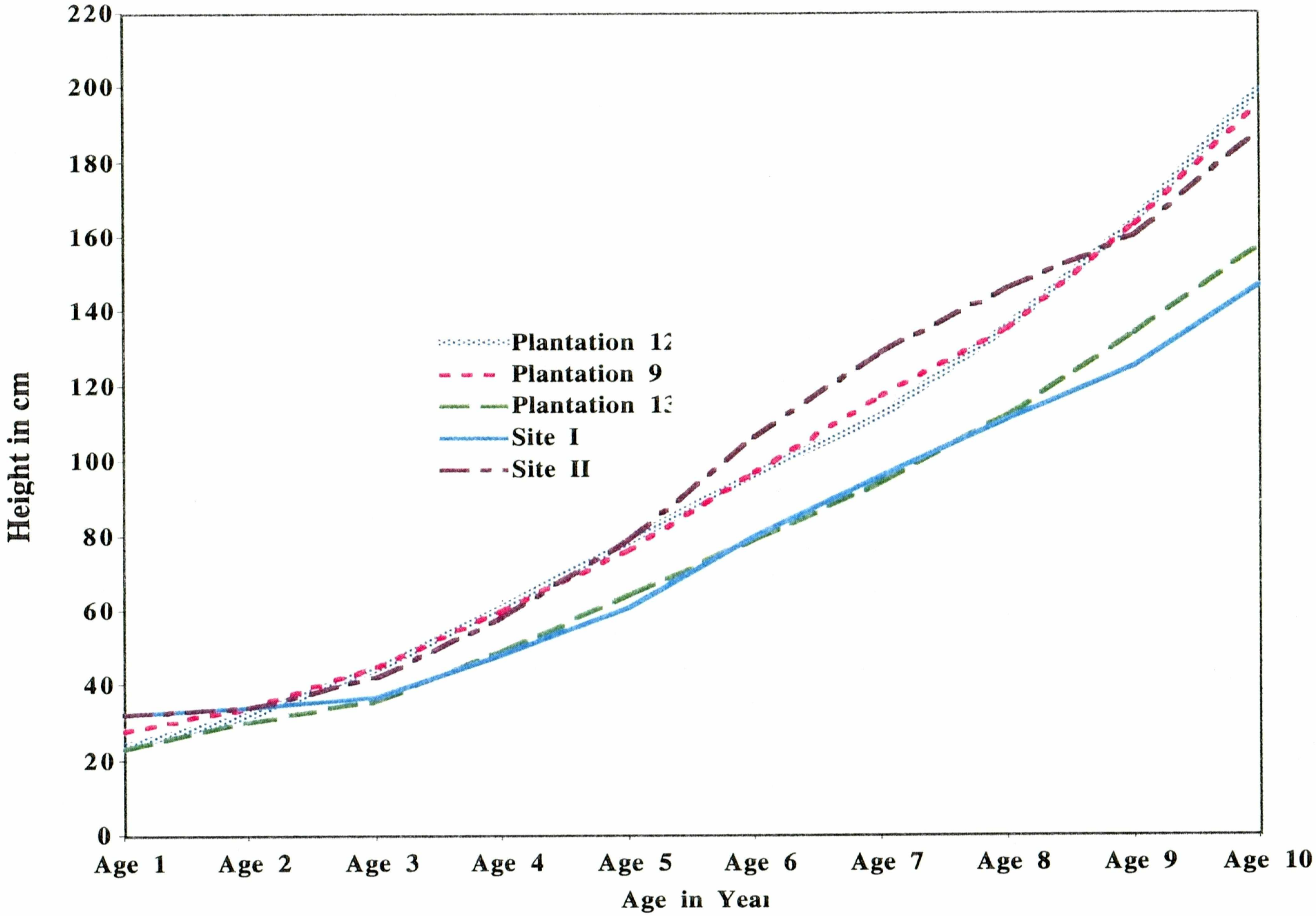

Figure 4.6. Mean annual total height data for Operational Plantation 9, 12, 13, LOGS Site I, and LOGS Site II.

factors become important. Supporting data presented here, Ruess et al. (1996) found that fine root production was greater in early successional stands in uplands compared to lowlands. It is, therefore, possible that the differences in height growth rate caused by slope position can be attributed to fine root production since the plantations studied have a maximum age of 12 and can be considered early successional.

Previous research on white spruce development placed considerable effort on understanding the effects of competition (Bella 1971; Eis 1980; Harvey et al. 1993). These studies showed significant reduction in the development of white spruce seedlings as a result of competing vegetation. The path analysis presented here also points to the negative impact of competition on white spruce development (Table 4.3). However, the regression model had a high unexplained variance (U = 0.94), which also indicates that there are potentially other variables besides aboveground competition that are important to successful white spruce growth. These factors could include soil pH, which affects phosphorus availability (Brady 1999), decomposition rates (Ruess et al. 1996), belowground competition, and species to species competition.

Competition is a very complex issue that was simplified considerably in this study. In this study competition was based on a scalar value by visually assessing the amount of "competing" vegetation. The amount of "competing" vegetation that is present on a site does not give a good indication of the potential below-ground competition on a site, nor does it address the issue of what species the white spruce seedlings were competing with. Belowground competition (i.e., competition for nutrients) is often important ecosystem driver (Tilman 1985) because it affects soil fertility, nutrient cycling and species composition (Berendse et al. 1992; Chapin et al. 1986; Grime 1973). In addition many studies have shown that a plant species may compete well with another species under certain environmental conditions but not under another set of environmental conditions (e.g., Nettleton 2000; Tilman 1987). To be properly assessed, competition needs to be more fully described in the field. Species composition of the "competing" vegetation and an indication as to what the seedlings are "competing" for (i.e., nutrients or light) would greatly add to the path analysis model and decrease the unknown variance that is if competition can be adequately measured.

The regression model for competition = slope position + aspect + percent slope + soil moisture + U was significant with all variables contributing significantly to the model. Percent slope was the most influential variable that was measured, as slope increases competition decreases. The exact relationship between percent slope and competition is unclear. Brand and Janas (1988) used a multi-factor experiment to examine the effects of soil temperature, fertilizer, and brush competition on the development of white spruce. They found that the only significant variable affecting white spruce development was soil temperature; as soil temperature increased, growth increased. The path analysis model presented here questions these results because of the high indirect effect that competition has on all other variables measured. Percent slope is a good indirect measure of radiation and soil temperature and, therefore, results presented here are in agreement with this. The second most influential variable was soil moisture, as the sites become better drained (drier) there were reduced levels of competition. These results agree with Grime's principle of competition/stress/disturbance (Grime 1977).

When a system is under lowered levels of stress (i.e., when there is more water available) there will be increased levels of competition.

Aspect was the third most influential variable in the competition model, and is also a very important factor when looking at regeneration and how it will affect the competing vegetation (Barr 1930). High latitudes can exaggerate the effects of aspect (Van Cleve et al. 1996). Unknown factors once again contributed greatly to this model, indicating that other variables not measured are important to competition. These factors could include leaf area index (LAI) the area that interacts with solar radiation, decomposition rate, and available nutrient supply.

The regression model for soil moisture = slope position + aspect + percent slope + U was also significant. The effect of percent slope on soil moisture is straightforward, as slope decreases soil moisture increases (Petrone et al. 2000) however, this model has little importance to height growth since it was established earlier that soil moisture does not significantly contribute directly to height growth rates.

Different dependent variables and the relationships among the dependent variables considered here affect early height growth rates. Past research has focused on experiments examining single effects on white spruce height growth in an attempt to estimate whether there is a positive or negative effect of a particular treatment (e.g., Bella 1971; Racey and Hutchison 1983). These past studies provide limited simplified results. The hypothesized path diagram demonstrates, that even when measuring a few variables that have been shown to affect height growth that the interactions of these few variables can make it difficult to single out the one or two most important variables affecting height growth. In fact, by performing a complex multivariate procedure which included multiple variables and the direct and indirect effects of these variables, these "single-factor" models may be misleading unless they were set up in completely controlled settings (Jongman et al. 1995).

The effort reported here addressed five environmental variables that were thought, *a priori*, to be important controls of white spruce height growth. Path analysis, however, showed that other factors contribute to the variance in height growth observed at different plantations around Fairbanks. To fully assess white spruce growth rates accurately and the environmental factors contributing to differences, a more intensive sampling scheme should be performed. This scheme should include soil factors such as pH, soil texture, carbon, nitrogen, and phosphorus, CEC, and organic matter content, as well as decomposition rate, a more sensitive competition scalar; LAI or some other measure of light; and a floristic survey that includes presence and cover all vascular and non-vascular species.

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V. SUMMARY AND CONCLUSIONS

White spruce is currently the most economically viable species in interior Alaska and, therefore, research addressing the early height growth trends after planting is essential to resource managers. The information presented here provides initial height growth patterns for experimental plantations and operational plantations as well as some insight on potential variables affecting height growth of white spruce in interior Alaska. Results suggest the variables collected (i.e., variables known to significantly affect white spruce development) were in fact, shown to be statistically significant on height growth rates.

Objectives of this thesis were two-fold: 1) Address the effects of espacement (density at time of planting) on annual total height of white spruce planted in two experimental plantations in Interior Alaska; 2) Compare annual total height in local operational plantations with the experimental plantations and determine the contribution a suite of site characteristics have on height growth rates of white spruce seedlings.

Early height growth analysis incorporates many complex variables. Studies focusing on one or two effects might be over-simplifying the issues affecting early height growth. For example, when seedlings are first planted they can exhibit periods of abnormally slow height growth, a phenomenon known as “planting check”. Planting check was suggested by results from the LOGS study where the first two years of annual total height was small. Showing that even carefully thought out experiments can have flaws.

This study also points to the significant effects of aspect and density on the "long-term" height growth trends of white spruce. Although the results do not point to a single most influential variable that would enhance our ability to predict height growth patterns of white spruce, the data do show estimates of growth potential for planted white spruce seedlings in interior Alaska. Especially important is documenting that the time needed for planted seedling to reach breast height (1.4 m) can be as early as 8 growing seasons but not more than 10 growing seasons after planting.

Phase One: Experimental Espacement:

Based on the LOGS study, ten years after planting, I can state with confidence that in a controlled experimental setting, both aspect and density have significant effects on white spruce height growth.

- After age 1, Site 1 had significantly less mean annual total height than Site II when all espacement plots and all replications were combined for the site (Table 3.1 and Figure 3.4). This was attributed to aspect differences.
- Significant differences in mean annual total height existed between some espacement plots for all ages at Site I. Significant differences in mean annual total height existed between some espacement plots for all ages except age 9 at Site II (Table 3.2 and Figures 3.5 - 3.6). At age 10 the widest (3.75 X 3.75 m) and narrowest (1.25 X 1.25 m) espacement plots demonstrated the least total annual height at both sites.
- Seedlings at Site I reached breast height during the 10^{th} growing season while at Site II Seedlings reach breast height during the 8^{th} growing season (Figure 3.7).

Phase Two: Operational Plantations:

The results of operational plantation study showed differences in annual total height among sites around Fairbanks area and examined the possible environmental variables responsible for these differences.

- Significant differences in mean height existed between some operational plantations at all ages (Table 4.1 and Figure 4.2)
- The LOGS sites were comparable in annual total height with the operational plantations after age 2, however a cause of the difference before age 2 was suggested for (Table 4.2 and Figure 4.3)
- Seedlings on operational plantations reached breast height between the 8^{th} and 10^{th} growing seasons, which was the same range of growing seasons needed by the experimental plantations.
- A hypothetical path diagram was developed to describe factors affecting white spruce seedling growth rates in interior Alaska (Figure 4.3).
- All three regressions used in the path diagram showed statistically significant direct effects (Table 4.3 and Figure 4.4) of the environmental variables measured. These results simply reinforce the complexity of ecosystems interactions on white spruce seedling development by leaving 90 percent of the variance unexplained.

Forest management would greatly benefit from a better understanding of height growth trends of white spruce in interior Alaska. To better understand these trends, comparisons of Alaskan height growth data and data from non-Alaskan locations throughout the range of white spruce should be performed. Ample long-term data sets are available on both experimental and operational plantations throughout Canada and the Great Lakes region of the US.

Upon viewing complex ecological systems in which white spruce grow, it is imperative that foresters and land managers have a sound understanding of ecosystem structure and functioning, in terms of regeneration. The regeneration of a forest stand is the single most important aspect of forestry; therefore without the necessary background in ecology, forest managers can over-simplify factors affecting seeding establishment and early development. In the words of Dr. E.C. Packee, "A good forester has to be a darn good ecologist…".

VI. APPENDICES

A. Appendix A

Table A.1. Degrees of Freedom (DF), Sum of Squares (SS), Mean Square (MS), F-value (F) and significance of F (Pr>F) of the ANOVA run on annual total height of the LOGS sites.

	DF	SS	MS	F	Pr > F
Age 1	1	4.1717	4.1717	0.08	0.7808
Age 2	1	572.67	572.67	11.15	0.0009
Age 3	1	18413	18413	236.2	<0.0001
Age 4	1	82320	82320	480.2	<0.0001
Age 5	1	227577	227577	601.9	<0.0001
Age 6	1	461336	461336	688.9	<0.0001
Age 7	1	699355	699355	712.9	<0.0001
Age 8	1	790583	790583	619.6	<0.0001
Age 9	1	828224	828224	508.5	<0.0001
Age 10	1	1103843	1103843	506.5	<0.0001

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Table A.2. Degrees of Freedom (DF), Sum of Squares (SS), Mean Square (MS), F-value (F) and significance of F (Pr>F) of the ANOVA run on annual total height of the LOGS Site I.

	DF	SS	MS	F	Pr > F
Age 1	4	1998.98	499.75	9.49	<0.0001
Age 2	4	1837.97	459.49	9.18	<0.0001
Age 3	4	1966.85	491.71	8.09	<0.0001
Age 4	4	2889.50	722.38	5.81	<0.0001
Age 5	4	8118.27	2029.6	7.30	<0.0001
Age 6	4	21740.1	5435	9.58	<0.0001
Age 7	4	42850.1	10712	12.21	<0.0001
Age 8	4	72784.7	18196	15.53	<0.0001
Age 9	4	152098	38024	25.95	<0.0001
Age 10	4	337691	84422	44.62	<0.0001

Table A.3. Degrees of Freedom (DF), Sum of Squares (SS), Mean Square (MS), F-value (F) and significance of F (Pr>F) of the ANOVA run on annual total height of the LOGS Sites II.

	DF	SS	MS	F	Pr > F
Age 1	4	3510.07	877.51	17.08	<0.0001
Age 2	4	3090.41	772.60	15.66	<0.0001
Age 3	4	3261.73	815.43	8.93	<0.0001
Age 4	4	4319.55	1079.9	5.07	0.0005
Age 5	4	6108.19	1527.0	3.27	0.0112
Age 6	4	6018.92	1504.7	1.99	0.0933
Age 7	4	9218.25	2304.6	2.19	0.0678
Age 8	4	10589.4	2647.3	2.00	0.0924
Age 9	4	11717.7	2929.4	1.75	0.1372
Age 10	4	30452.8	7613.2	3.47	0.0080

B. Appendix B

Table B.1. Degrees of Freedom (DF), Sum of Squares (SS), Mean Square (MS), F-value (F) and significance of F (Pr>F) of the ANOVA run annual total height of operational plantations in the Fairbanks area.

	DF	SS	MS	F	Pr > F
Initial ht	13	4344	334	15.07	<0.0001
Age 1	15	2084	1359	27.12	<0.0001
Age 2	15	46618	3107	35.12	<0.0001
Age 3	15	113123	7542	41.06	<0.0001
Age 4	15	209558	13971	44.15	<0.0001
Age 5	15	291758	19451	37.85	<0.0001
Age 6	11	31376	28471	32.19	<0.0001
Age 7	6	276051	460009	38.91	<0.0001
Age 8	4	313807	78452	50.92	<0.0001
Age 9	2	86863	43432	19.87	<0.0001
Age 10	2	161992	80996	28.01	<0.0001
Age 11	2	213185	106593	27.03	<0.0001
Age 12	1	196158	196158	38.47	<0.0001

C. Appendix C

Table C.1. Degrees of Freedom (DF), Sum of Squares (SS), Mean Square (MS), F-value (F) and significance of F (Pr>F) as well as the Parameter Estimates of the Regression run on growth rate of operation plantations for the first model.

	DF	SS	MS	F	Pr > F
Model 1	5	9861.2	1972	51.06	<0.0001

Variable	DF	Parameter Estimate	Standard Error	T--Value	Pr < |t|	Standardized Estimate
Intercept	1	18.148	1.202	15.10	<0.0001	0.0
Competition	1	-1.858	0.244	-7.60	<0.0001	-0.166
Slope Position	1	2.571	0.243	10.58	<0.0001	0.224
Soil moisture	1	-0.015	0.286	-0.05	0.9578	-0.001
Percent Slope	1	-0.168	0.022	-7.54	<0.0001	-0.185
Aspect	1	-0.242	0.171	-1.41	0.1578	-0.031

Table C.2. Degrees of Freedom (DF), Sum of Squares (SS), Mean Square (MS), F-value (F) and significance of F (Pr>F) as well as the Parameter Estimates of the Regression run on growth rate of operation plantations for the second model.

	DF	SS	MS	F	Pr > F
Model 2	4	75.48	18.12	58.17	<0.0001

Variable	DF	Parameter Estimate	Standard Error	T--Value	Pr < |t|	Standardized Estimate
Intercept	1	3.243	0.081	39.98	<0.0001	0.0
Slope Position	1	-0.132	0.022	-6.11	<0.0001	-0.128
Soil moisture	1	-0.234	0.025	-9.31	<0.0001	-0.229
Percent Slope	1	-0.199	0.002	-10.24	<0.0001	-0.247
Aspect	1	0.099	0.015	6.48	<0.0001	-0.142

Table C.2. Degrees of Freedom (DF), Sum of Squares (SS), Mean Square (MS), F-value (F) and significance of F (Pr>F) as well as the Parameter Estimates of the Regression run on growth rate of operation plantations for the third model.

	DF	SS	MS	F	Pr > F
Model 3	3	199.59	66.52	279.60	<0.0001

Variable	DF	Parameter Estimate	Standard Error	T--Value	Pr < |t|	Standardized Estimate
Intercept	1	2.348	0.049	48.29	<0.0001	0.0
Slope Position	1	-0.055	0.019	-2.91	0.004	-0.054
Percent Slope	1	-0. 35	0.002	-22.93	<0.0001	-0.439
Aspect	1	0.144	0.013	-11.14	<0.0001	-0.212